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Time for Growth

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Abstract

This paper studies the impact of the early adoption of one of the most important high-technology machines in history, the public mechanical clock, on long-run growth in Europe. We avoid endogeneity by considering the relationship between the adoption of clocks with an instrument based on the appearance of repeated solar eclipses. This is motivated by the predecessor technologies of mechanical clocks, astronomic instruments that measured the course of heavenly bodies. We find a significant increase in growth rates between 1500 and 1700 in the range of 30 percentage points in early adopter cities and areas. Finally, additional quantitative analysis suggests a positive relationship between mechanical clocks and contemporary long-term orientation nowadays.

Keywords: technological adoption, cities, mechanical clocks, information technology, long-term orientation

JEL classification: 033, N13, N93.

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1 Introduction

This paper investigates the impact of the early adoption of high-technology machines on long-run growth. Various studies have widely discussed the possible benefits and drawbacks of the role of high-technology innovation on firms and nations economic success. On the one hand, a well-established literature by various scholars (e.g., Ricardo (1821), Leontieff (1983), Samuelson (1988), and Zeira (1998)) has claimed that the impact is negative because advanced machines lower wages, which in turn reduce population and income growth. On the other hand, in the past twenty years, which coincide with the introduction of new innovations in information technology (henceforth, IT), new research has found a more differentiated picture of this relationship. In a 1987 article published in the *New York Times*, Robert Solow underlined a productivity paradox (also known as the Solow Paradox), which highlights that the American productivity slowdown in the 1970s concurs with the adoption of computers (*"You can see the computer age everywhere but in the productivity statistics."*). However, other scholars have found the advantage and the positive effects of the spread of computers on society: Bresnahan et al. (2002) underline the positive role of high tech capital and the complementarity with skills and innovations at the firm level; Caselli and Coleman (2001) use country data and find a strong and positive relationship between human capital, computers and productivity; Andersen et al. (2012), examine the negative role played by lightning in IT diffusion and explain the higher economic growth across American states due to digital technologies. In contrast, more recently Acemoglu et al. (2014) confirm a Solow Paradox in IT-intensive sectors, where an increase in labor productivity is associated with a decline in employment. Some main problems with these types of studies is that they have to address several empirical challenges. First, it is difficult to identify the adoption of IT at the micro level and to create a representative aggregate picture at the macro level. Second, the identification of adoption does not necessarily guarantee the accurate use of the new technology. Finally, the time series for potentially identifying growth are relatively short.

To find an answer to the question concerning the relationship between technology and economic performances, case studies based on the introduction of innovative machines can be useful. In an early reply to Solow, the economist and economic historian Paul David (1990 and 1991) suggests resolving the study of the Solow Paradox from a historical perspective. Examining the innovation of the dynamo in the late 19th century he argues that it simply takes time until the use of such a general purpose technology (GPT, henceforth)[1] affects economic growth rates. As described by several studies,[2] gains in efficiency due to new technologies can increase over time because of the gradual replacement of the old technology with the new one and the intergenerational learning-by-doing process of the workers. Crafts (2002), among other scholars, took up this line of argumentation and compared the impact of different GPTs, such as electricity and computers, on long-run economic growth. He finds comparably strong evidence for the effect of IT, but admits that there are problems in measuring and comparing such effects adequately. A more recent study related to the different impact of technologies on American growth dynamics after the Civil War has been done by Gordon (2016). Going further back in time, Dittmar (2011) finds that the invention and diffusion of the printing press during the 15th century had a long-run growth effect (between 1500 and 1800) at the city level, since the possibility to print media, which increased the dissemination of ideas, facilitated human capital accumulation and helped business practices.

These findings by Dittmar (2011) can be related to a broader process of social and cultural change observed by Crosby (1997), who relates medieval and premodern technological innovations to a change in the perception of the world from a qualitative to a quantitative perception. Such a claim can already be found in Le Goff (1971), who identifies a changing environment during the late Middle Ages in "atmosphere of calculation". However whereas Le Goff attributes such a change already to the late Middle Ages, Crosby emphasizes the long-run process starting during the late Middle Ages and only fully accelerated by the end of the 16th century. Important is that the technological change triggers and coevolves with cultural and social change. Only the development of both might enfold growth and development of a society.

In this paper, we attempt to shed light on potential productivity paradoxes from a new perspective. We study the impact of one of the most important technologies ever invented in history, i.e., the public mechanical clock, on economic growth. This technology was first introduced in Europe at the end of the 13th century, and it spread across Europe during the subsequent two centuries. Mechanical clocks have been identified as one of the greatest technological inventions of the last millennium.[3]

[1] Bresnahan and Trajtenberg (1995) define GPTs according to three characteristics: first, they should be pervasive in most economic sectors; second, they should improve over time with lower costs for the consumers; finally, they should incentivize new products and processes.

[2] See, for example, Devine (1983), Atkeson and Kehoe (2007), and, for a summary, Weil (2013)'s textbook on economic growth.

[3] The public mechanical clock fulfills many of the attributes described by Bresnahan and Trajtenberg (1995) as previously mentioned. For an identification of the clocks as a GPT see Comin et al. (2010) and Weil (2013). However,

The importance of mechanical clocks has been discussed by several scholars in different fields. Landes (1983) claims that clocks were the technological sensation of the 14th century, which is similar to computers today. Furthermore, he argues that the clock had a strong impact on productivity: it enabled increases in organizational skills in terms of the coordination and division of labor and the monitoring of production processes. Very much in line with Landes, Mokyr (1992) argues that the mechanical clocks was one of the most important technology inventions of the last millennium. Moreover, Thompson (1967) highlights that the mechanical clock overlapped with a changed work culture and increased work discipline. Le Goff (1982) claims that the introduction of the public mechanical clock was a turning point for the Western society. It helped create a new epoch, "the time of the merchants", because it enabled business people to better frame and measure all types of economic activities in a timely manner. In addition to the already discussed points, Dohrn-van Rossum (1996) finds evidence for the improvement of various coordination activities in premodern towns such as market times, administrative meetings of the town governments, and school and university lecturing times. Other economic historians with a greater focus on the transition to modernity, e.g., Mumford (1934), Rosenberg and Birdzell (2008) and Voth (2001), argue that the clock had a profound impact on the processes of the Industrial Revolution. Mumford even describes the mechanical clock, and not the steam machine, as the key machine of the the modern industrial age because the knowledge accumulated from the mechanical clock had a positive spillover during the Industrial Revolution. Furthermore and more generally, prominent social scientists such as Marx (1863), Weber (1905) and Sombart (1921) claim that clocks had a fundamental impact on the evolution of capitalism and the rationality of societies.

Most of these studies have in common that they emphasize the strongly time-lagged impact of the clock, i.e., the technology took several centuries to develop any economic (or cultural) influence on societies. They claim that the learning and use of new forms organization and coordination of production related to the clock could only develop embedded in a change in work culture, for instance, in the form of punctuality and discipline. Furthermore, the introduction of clocks was not related to any economic needs but was a sign of prestige and progressiveness, thus showing one to be at the technological frontier. Therefore, the clock indeed would be an excellent investigation subject

the clock differs since it misses the technical complementarities to other technologies, but remained a stand-alone technique. However, it did have the important effect of creating a new high-skill and precision industry (Mokyr (1992)).

for testing the Solow Paradox. In addition, we would not have any issues with endogeneity when considering the direction of causality, i.e., that economic growth would not spur the introduction of public mechanical clocks. Both claims have been derived based on qualitative studies and thus need rigorous quantitative analysis. Thus, examining this enumeration of findings and claims made by this large number of scholars we should find some long-run growth effects based on changes in organization, production, and work culture. This means that the introduction of clocks in medieval cities should have localized spillover effects in these towns and further affect growth at a more aggregate level.

To test the impact of clocks on economic growth, we construct a unique dataset collected from several historical sources. To study economic growth, we use the dataset of European city sizes collected by Bairoch et al. (1988). We use population size over time as a proxy of cities' welfare to study the trajectories of premodern economic growth (Acemoglu et al. (2005b)). Our dataset contains all cities for which population was recorded from 1000 to 1850. Our central explanatory variable is the information we have collected on the construction of public mechanical clocks in these cities. We identify a group of early adopting cities from the first adopters in 1283 until 1450. The end point is calculated based on the inflection point and hazard rate of the S-shaped diffusion curve of mechanical clocks. Based on this identification we measure the impact of the implementation of clocks by early adopters compared to other cities. We study population size from 1000 until 1850 and control for a broad set of variables, including the institutional and geographical characteristics of cities and regions. Our dataset has several favorable characteristics and is not affected by sample selection because the construction of clocks is well documented in the available source material. Therefore, we have a representative and rather complete sample on the date of the adoption and geographical location of this new technology. Clocks were affordable and had relatively low maintenance costs (as we will discuss later). Thus, once installed, clocks were used and maintained by the city population over many centuries. Furthermore, clocks were nonexclusive public goods that were easy to understand and use by an entire city's population. Finally, our study allows us to have a very long-run perspective on the effect of this technology on economic growth.

Our empirical strategy includes various standard approaches used in the related empirical literature. We consider the estimation of a standard differences-in-difference regression as benchmark. We also address endogeneity problems between the size of the city and the adoption of clocks, missing explanatory variables, and measurement errors of the main explanatory variables by employing an instrumental variable approach based on the presence of total and annular eclipses. We exploit data constructed by the National Aeronautics and Space Administration (NASA, henceforth) for detecting populated geographical area intensively covered by solar eclipses before the adoption of the first clocks. The use of solar eclipses as an instrument for clocks is motivated by two types of observations by science and technology historians: first, eclipses and other astronomic movements created curiosity in societies, influenced the study of astronomy and triggered the construction of mechanical devices that aided in measuring these astronomic events, such as astrolabes and specially designed water and sun clocks (Turner (1911) and Dohrn-van Rossum (1996)); second, these machines have been identified as the predecessor technologies of mechanical clocks. Finally, we consider different robustness of our results. In particular, placebo tests based on different sets of past (i.e., from 2000 B.C. to 800 A.D.) and future (i.e., from 1450 A.D. to 3000 A.D.) eclipses provide additional support on the connection between the eclipses and the adoption of the clocks.

Following the proposed methodologies, we find that earlier adopters, compared to other cities, displayed a significant increase in population growth during the period of 1500-1700. These robust results indicate that the new emerging technology of public mechanical clocks indeed localized spillover effects on various social and economy-supporting activities and led to higher city growth rates in the long-run until new substitute technologies (such as the portable watch and the pendulum) were introduced in the 18th century. To further substantiate our findings, we make some more extensive robustness checks. First, we investigate whether the introduction of a subsequent technology in the form of the printing press affects our results. However, both technologies have a strong effect and our previous results do not change. Second, using an alternative instrument, in the form of the distance to the first innovators, provides similar results. Third, we test the relationship between the adoption of the public mechanical clock and the population exploiting a propensity score matching technique without any alterations of the results. Fourth, we test whether our results are affected by particular subsets of the dataset considered. We run an entropy test (Hainmueller and Xu (2013)), and in this, the results are also consistent. Finally, we exploit the time of adoption as additional information for our estimation. We run an event-study regression analysis (Autor (2003)) and find persistent effects over several centuries after the introduction of the clock.

Complementary to this city-level analysis we do a robustness check on the macro level. We use the penetration rate of the new technology on the country-level to estimate the GDP-growth rate of a country. As an instrument, we use the share of the population covered by solar eclipses. Econometrically, we follow the methodology by Czernich et al. (2011) and find it again very similar to the microlevel.

Finally, we also compare our data on the diffusion of public mechanical clocks on contemporary cultural norms related to people's attitudes toward time. Studies in psychology (e.g., Levine (1998) and Levine and Norenzayan (1999)) underline how different paces of life are intertwined with biological and city's rhythm (Bettencourt et al. (2007)). Furthermore, we consider whether public mechanical clocks can influence long-term orientation, a value which is a relevant driver for conducting business and for the social life in general (Hofstede et al. (2010)). Simple correlations based on country-level data suggests a positive link between the early adoption of mechanical clocks and proxies for the pace of life. Very similar results are obtained once long-term orientation is studied. We also consider the regression framework introduced by Galor and Özak (2016) and exploit a dataset based on second-generation migrants from the European Social Survey, finding that mechanical clocks can have a positive long-run legacy for explaining long-term orientation.

Our findings contribute to the literature in the following ways. First, public mechanical clocks had a positive impact on economic growth and development. This is in line with the previously mentioned large body of literature that derives this conclusion based on qualitative studies on changes in economic institutions and organizations. For instance, Mokyr (1992) writes that mechanical clocks created order, organization, and a shared set of objective information. This improved the measurement of productivity, increased the efficiency among workers, and greatly affected other sectors. Our estimates indeed give evidence for higher economic output based on such changes. Our empirical results suggest a causal relationship between 1500-1700 when controlling for potential econometric estimation biases. During earlier periods closer to the first implementation of clocks, no such causal relationship can be found. This supports the claims have been made by the scholars who determined that the construction of clocks was not motivated by any economic needs. Second, our results shed light on the role of technology for economic development and growth before the Industrial Revolution. Our results provide evidence on the quantitative impact of technological change that was triggered by the upper-tail of human capital (Mokyr (2002 and 2005)) and Squicciarini and Voigtländer (2015)) that occurred well before the scientific revolution (Long (2011), Zilsel (2011), and Zanetti (2017)). The first clocks had been constructed by the so-called Vitruvian artisans, who had various backgrounds including crafts, engineering, and astronomy. Whereas a strand of literature has been developed that documents qualitative evidence of such a movement, the quantitative impact of this for the development has been highly debated and lacks any quantitative investigation to date. A more detailed analysis of the coevolution of various technologies in premodern Europe and their impact on Protestantism can be found in Boerner et al. (2019). Third, our analysis highlights the very long-run relationship between the technology and economic growth. This sheds further light on the Solow Paradox. Compared to other findings in the related literature (for instance, David (1990), and Crafts (2002)), the process from the implementation to the use of clocks took even longer. Finally, our paper contributes to the use of instruments in the empirical growth literature. To the best of our knowledge our paper is the first to introduce the appearances of solar eclipses as an instrumental variable.

The paper is structured as follows. Section 2 illustrates the introduction and diffusion of mechanical clocks and describes the potential links to economic growth. In addition, the instrument is explained. Section 3 describes the data collected. Section 4 introduces the empirical strategy for studying the impact of clocks at the city level. Section 5 provides further robustness check. Section 6 looks at the potential impact of the mechanical clock on contemporary culture. Finally, Section 7 concludes.

2 The mechanical clock

2.1 Introduction of public clocks

The introduction of public mechanical clocks can first be observed during the late 13th century. These clocks were typically built on church towers or the communal tower of the town, and they were mechanical devices that produced a weight-driven acoustic signal every hour. Thus, early mechanical clocks did not have a dial but worked only with a bell.[4] The day was typically divided into two units of twelve and the bells rang accordingly as many times. In some cities, other formulas such as four units of six were used. In this way, the clocks were publicly accessible and easy for everyone to understand. A person had only to listen to the chime and have the ability to count. The origin of these mechanical clocks cannot be precisely documented. However, two main hypothesis have been formulated. In one hypothesis, the innovation developed out of scientific curiosity and the need

[4] The introduction of complementary dials is frequently documented from the beginning of the 15th century (Dohrn-van Rossum (1996)).

to keep time in the European monastic life (Landes (1983) and Dohrn-van Rossum (1996)). Time keeping was particularly important for the study and measurement of the courses of the celestial bodies. The assumption of this approach is that the monks had basic knowledge of water clocks, sun clocks, and existing astronomic instruments, particularly the astrolabe. Such knowledge must have been transmitted through either via old Roman and Greek sources or more recently from the fairly well-developed scientific body of knowledge of Arabic scientistis, who were leading astronomers during the late middle ages. This body of knowledge was accessible to the Europeans. However, the critical step, which was the introduction of the weight-driven mechanism with an escapement and regulation, was developed in Europe. A few sources indicate the imminent discovery during the second half of the 13th century but do not reveal the crucial step of discovery. For example, Thorndyke (1941) reports the existence of an astrolabe that closely resembles the mechanical clock. The second hypothesis is that the technology had already been sufficiently developed by the Chinese scholars in the form of astronomic clocks (which, however, were driven by hydraulic mechanisms) and that the information on their construction had been vaguely transmitted via Indian or Arabic travelers to Europe (Price (1956) and Needham (1986)). By using their knowledge, simplifying their astronomic instruments, and creating a different mechanical engine, the European scholars created the mechanical clock. The two hypotheses share the notion that the innovation was strongly driven by scientific curiosity in general and by the interest to better understand the constellations of the heavenly bodies and to further develop astronomic instruments in particular. We will consider this link in more detail when we discuss the appropriate instruments for the econometric analysis.

2.2 The diffusion of mechanical clocks between 1283 and 1450

Dohrn-van Rossum (1996) identifies the time interval from the first adoptions to 1450 as the period of the early adoption of public mechanical clocks. In addition, he divides these decades into three phases based on the areas and intensity of diffusion in Europe. The first adoption phase covers the period until 1350. During that time, the few public mechanical clocks were mainly built in cities in Italy in the area of the Papal States and Northern Italy (which partly belonged to the Holy Roman Empire), in England, and in the Holy Roman Empire north of the Alps. In the second phase, 1350-1370, a stronger diffusion in the mentioned areas can be found. Further diffusion in French and Dutch cities can be observed. In addition, a few observations in Spain and Sicily are documented. Furthermore, in the third phase, 1370-1450, further and strongly booming diffusion in the already covered areas is documented. Finally, in neighboring eastern European areas and Scandinavia, the diffusion process also began.

The motivation for the diffusion of public clocks in late medieval towns (at least during the 14th century) was mainly prestige (Bilfinger (1892), Sombart (1921), and Mokyr (1992)). The clocks were financed by the towns, worldly and ecclesiastical dukes and other wealthy noblemen of the towns. A clock was the pride of a city and showed the openness and progressiveness of a town. As Truitt (2015) remarked, the status symbol effect is also mirrored by the exterior design and other functions of the clock, where the time and the astronomical information are often juxtaposed to perpetual calendars, carillons, different type of mechanical movements and paintings showing religious figures. Economic motivations in terms of merchants needs, as suggested by Le Goff (1982) cannot be identified in corresponding source material during this early phase of adoption and only evolved over time (Dohrn-van Rossum (1996)). The construction and maintenance of a clock was compared to other public expenses not that costly (however not neglectable and typically mentioned in the town account books) as the following example of the city of Duisburg in 1401 suggests. Duisburg is a rather smaller town in our sample. Looking at the town account books, the construction and installation of the first clock cost 10 Gulden. The daily maintenance cost 2 Gulden per year (paid as yearly wage to the local sexton), and a general overhaul, which took place every couple of years (normally carried out by a foreign expert), cost approximately 10 Gulden. In comparison, the complete renovation of the church tower roof in the year 1401 cost 60 Gulden. The new church cross cost 35 Gulden in 1365 (Mihm and Mihm (2007)).[5]

Furthermore, no special materials were needed. The clock comprised wood and iron, which was broadly available in medieval towns. More importantly, the towns depended on clockmakers who were able to build the fine mechanic that was essential to construct a clockwork. Clockmakers were for a very long time not an established profession or even organized in guilds. Early clockmakers came from various professional backgrounds. In some cases, they had an expertise in astronomy; others were

[5] An earlier example of building costs was handed down from of the building of the Canterbury clock in 1292: it cost approximately 30 Pounds, which was approximately 10 times the yearly salary of a skilled worker, for instance a carpenter. Comparing related building costs, the church account book mentions that the reparation of parts of the gable cost 13 pound in 1294 and a major rebuilding of the choir and some other parts cost 840 pounds in 1304 (Dart (1726)).

self-taught engineers, or talented smiths with expertise in fine mechanics (Dohrn-van Rossum (2005)). Clockmakers typically travelled from one city to the next, and shared their expertise with locals, who became clockmakers themselves or were at least able to support the maintenance of the machine. Finally, no other hindrances can be documented that prevented the spread of clocks in Europe. In particular, Dohrn-van Rossum (1996) states that the church "did not hesitate in introducing and making practical use of the new technology as soon as it was available."

Exploiting our dataset on the adoption of clocks (described in the next section) and the GIS national borders provided by Nuessli (2011), we construct Figure 1 showing all the cities that adopted at least one public mechanical clock by 1450.[6] Detailed maps on the abovementioned stepwise process of diffusion can be found in Appendix A, where the dispersion of the mechanical clock technology in medieval Europe during the period of 1283-1450 is illustrated in periods of roughly thirty to forty years, i.e., 1283 until 1370, until 1380, and until 1410. A similar pattern as that described by Dohrn-van Rossum can be found by further statistical analysis: The left part of Figure 2 shows the cumulative distribution of the proportion of technological adopters using our dataset for the period of 1283-1600.[7] In this graph, we observe an S-shaped curve with a slow start in adopting the new technology and two structural breaks during the second half of the 14th and 15th centuries and beyond. This forms the typical diffusion curve of new technologies, as described in Rogers (2003)'s analysis of diffusion processes. Moreover, a more precise analysis based on the hazard rate (Young (2009)), which is shown in the right part of Figure 1,[8] shows that early adopters of the mechanical clocks were the cities that built this technology before 1450; the conditional probability, represented by the hazard rate, is almost equal to zero. Then, we can observe a strong acceleration in adoption. This result confirms the use of 1450 as an endpoint and defines the number of early adopters in our sample.

[6] Please note that our total sample contains all the cities covered by Bairoch et al. (1988) for which we have population data from 1000 to 1850.

[7] In Figure 2, we have a proportion of adopters that is lower than 70%. This can be explained by our consideration of the early adoption of mechanical clocks. It is estimated that the public clocks arrived in almost all the cities by the end of the 18th century.

[8] More precisely, we consider the strategy applied by Young (2009) on Griliches (1957)'s dataset. We define p_t the proportion of adopters a time t, and we define the hazard rate of adoption H_t, i.e., the conditional probability of adopting a mechanical clock as

$$H_t = \frac{p_{t+1} - p_t}{p_t(1-p_t)}$$

The right-hand side of Figure 2 shows the prediction of a cubic polynomial, $H_t = a + b_1 t + b_2 t^2 + b_3 t^3 + u$.

Figure 1: The diffusion of the mechanical clock in Europe in 1450. Source: Authors' calculations using the authors' dataset of clock and GIS border by 1400 from Nuessli (2011).

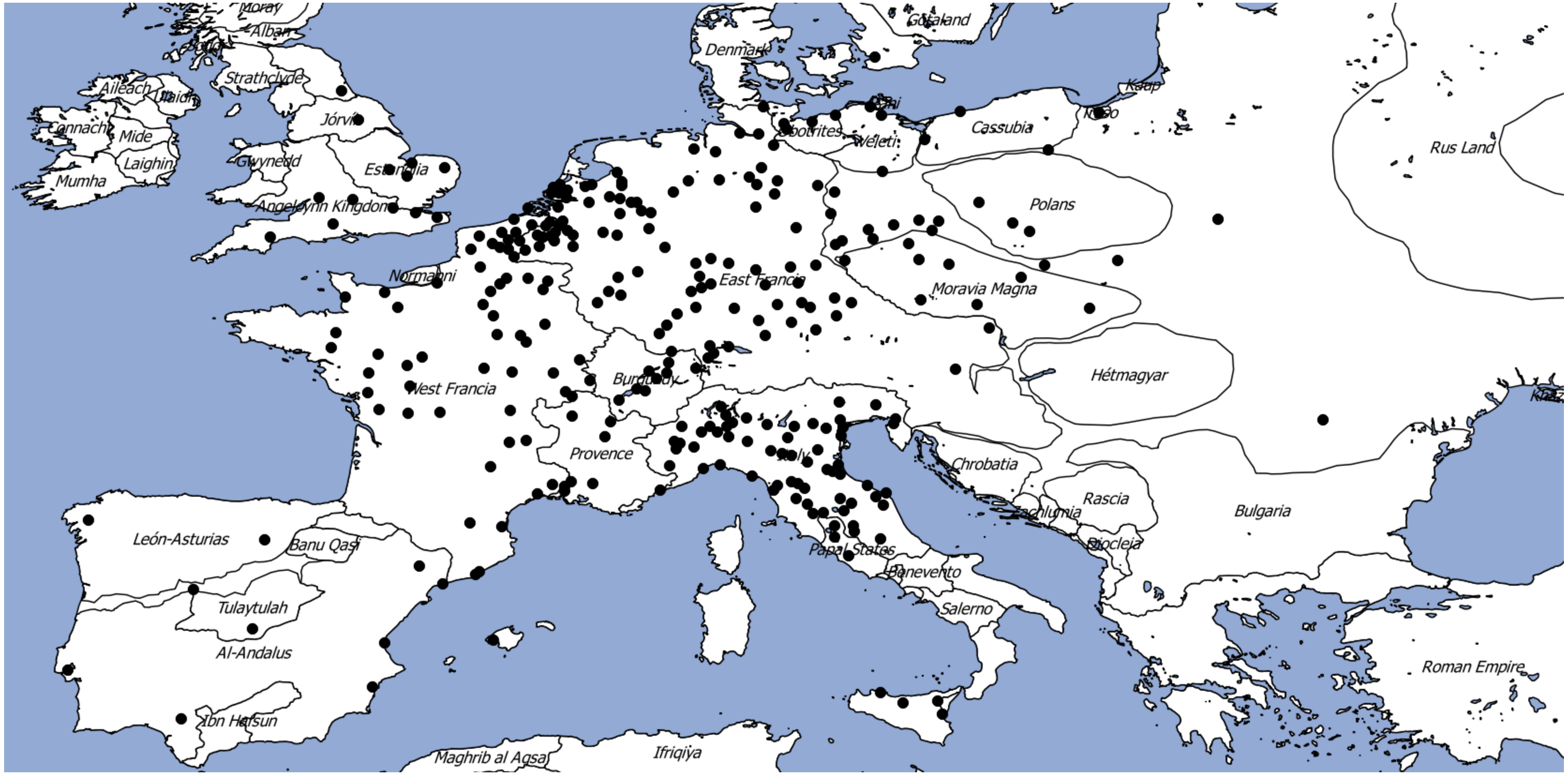
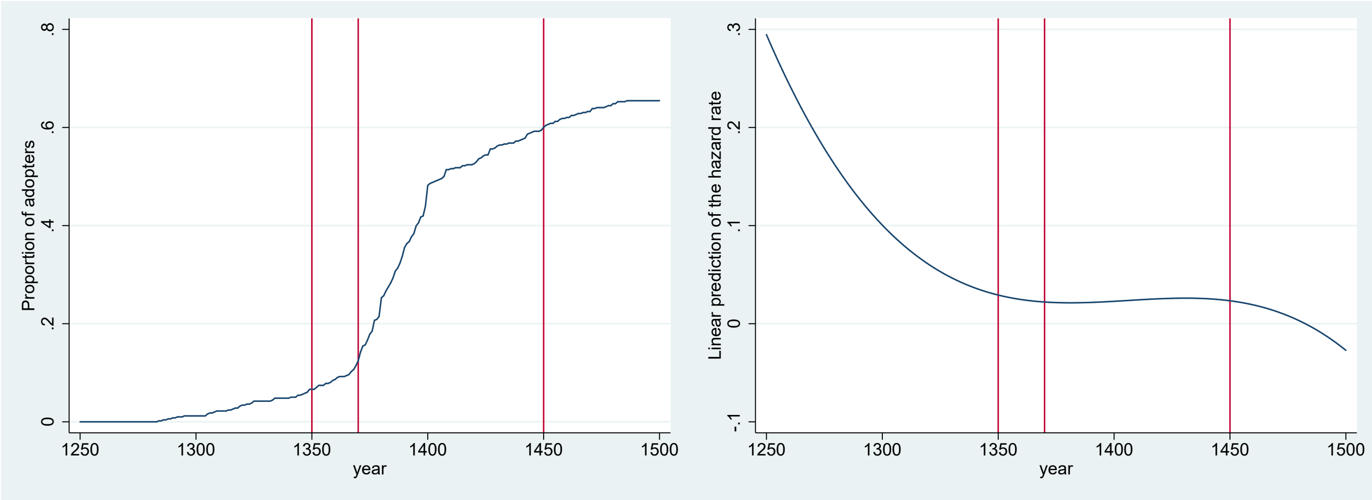


Figure 2: Diffusion of the mechanical clock in Europe between 1283 and 1500



Cumulative distribution of mechanical clock (left part) and linear prediction of the hazard rate described in Section 2.2 (right part). Source: Authors' calculations based on the authors' dataset of clocks. Cities available in the Bairoch et al. (1988) 's dataset. The vertical red lines represent the end of the three phases of early adoption (i.e., 1350, 1370, and 1450), as described in Section 2.2.

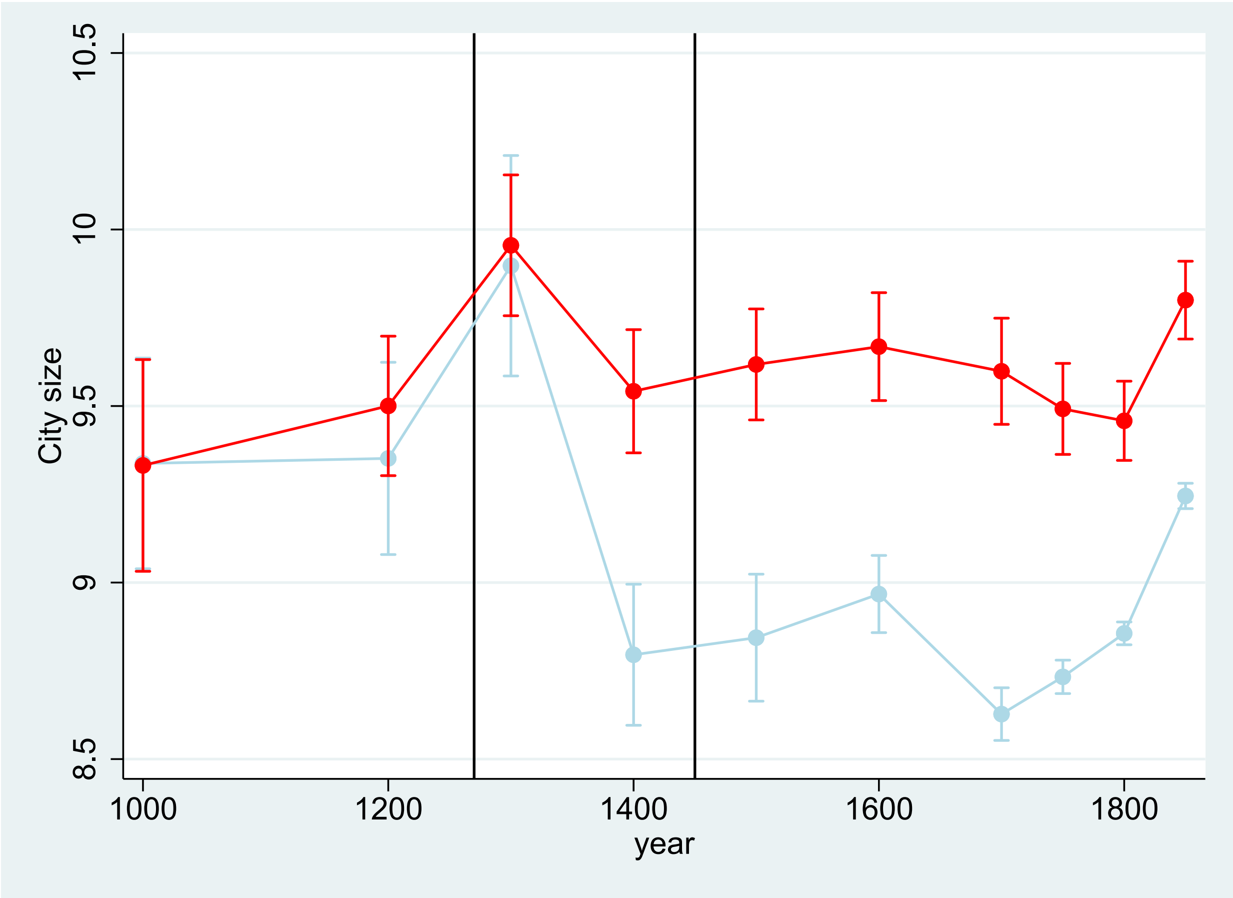
2.3 Mechanical clocks and economic growth

Figure 3 shows a stylized relationship between the early adoption of the public mechanical clock and cities' population size. More specifically, we consider the cities, included in the dataset of Bairoch et al. (1988), which have at least three consecutive observations available during the adoption period. We split our sample into two different groups: the first group is represented by cities that had adopted a clock between 1283 and 1450, while the second is represented by cities that had not. The figure controls for pretrend across the groups and shows that size is not a relevant variable before the introduction of this technology, while the two series diverge after 1300, showing that the clock adopters had a statistically significant higher average growth with respect to the other group.[9]

To better understand the process of adoption and growth, we need to proceed in three steps. First, we need to understand what the introduction of the public mechanical clock potentially offered to the European cities. Second, we must determine how this means of keeping time was different from previous means. Finally, we must identify the different channels of adoptions and applications that

[9]More precisely, before 1300 future adopters of a mechanical clock had an average of 23,300 inhabitants in contrast with 21,100 inhabitants of the other group. After 1300 adopters had an average of 27,000 inhabitants, while non adopters decreased their population size with 12,000.

Figure 3: City size and the adoption of the public mechanical clock



Unweighted average of cities' population with 95% confidence interval. The red line represents the adopters, the blue displays the non adopters of the mechanical clocks. Source: Authors' calculations based on the authors' dataset of clocks. Cities available in the Bairoch et al. (1988)'s dataset and with at least three consecutive observations during the adoption period.

made the clock valuable and could result in higher economic growth rates.

Answering the first question is rather straightforward. The clock offered an accessible and audible signal that divided the day into equally long units (Landes (1983)). To answer the second question a more sophisticated answer is needed. The concept of dividing the day into measurable subunits existed before the clock (Lippincott et al. (1999)). The division of the day into twelve parts dates back to ancient times. However, the length of the hour depended on the length of the day and was a fixed proportion of the sunlight hours (the so-called temporal hours). Thus, an hour could vary during the summer and winter periods. In line with this concept, the hour could be measured by sun clocks. However, because this measurement technique depends on time of the year and the weather conditions, the length of the hour varied and the technology was less reliable. Therefore, it was not intensively used in societies. Rather, people followed simpler indications such as the position of the sun, i.e., the sunrise, noon, and sunset, as guidelines. The concept of the division into twenty-four equally long hours (the so-called equinoctial hours) also dates back to ancient times. However, it was rather complicated to measure and could not be directly derived from the constellation of the sun, as it had to be derived by calculations. This division of time was mainly used to follow the course of the heavenly bodies. Astronomic instruments, so-called astrolabes, or specially calibrated water clocks were employed to measure these activities. The use of astrolabes to measure daily time was overly complicated, and the use of water clocks required additional calculations and a very precise calibration of the clock.[10] Therefore, the introduction of the mechanical clock improved the quality of time keeping dramatically.[11]

The use of bells as signals existed before the introduction of mechanical clocks (Dohrn-van Rossum (1996), chapter 7). In late medieval cities, it became popular to indicate and coordinate all types of social and economic activities with various bells, fanfares or flags. These signals were approved by the city government and were used for specific tasks and groups of people. Therefore, what was new with respect to the public mechanical clock was the introduction of a regular, repetitive, precise, and common signal for urban society that could be used for all types of signaling purposes. In this way, the multiplicity of signals, which in some cities reached their limits by the late Middle Ages and created chaos rather than order, could be replaced by one abstract signal.

Finally, the remaining question that needs to be answered is how the clock affected the daily life of the population and was transformed into higher economic output. Clocks had an effect on the organization and coordination of daily life activities with respect to economic, administrative and educational tasks. There exists evidence from the 15th century onwards that the public clocks were used to coordinate such activities in many cities (Dohrn-van Rossum (1996)).[12] The organization of markets neatly documents this change. Whereas prior to public clocks, the market time typically started with sunrise and ended at noon, with the introduction of clocks, market times were determined by the stroke of the hour. Furthermore, market time was shortened and market access was granted to dif-

[10] The use of water clocks can only be documented in a few sources in ancient Europe. There are references for ancient Rome, but the clock was likely calibrated based on the length of the day. Furthermore, we have some evidence that such mechanisms potentially existed in the neighboring Arabic world in the form of water clocks, which produced regular repeating sounds. However, according to the source material available, these machines were rather automates for entertainment and admiration. Finally, it is documented that medieval monasteries used water clocks.

[11] For a more detailed discussion of the quantification of this improvement, see Cipolla (1967).

[12] Härter (2007), in an extensive case study on on regulations in German Imperial cities and territories, finds a massive increase in regulations on market starting time, in particular, during the 16th century.

ferent groups of people at different times. For instance, market regulations offered time-differentiated access to consumers, retailers, and wholesalers, and in some cases, a differentiation between foreigners and locals or religious groups was made. Furthermore, we find evidence for the tight organization of administrative meetings of town officials following the signals of the public clock. Finally, schools and universities began to use the public clocks to determine the starting and ending times of lectures.[13] There were several potential economic benefits of such improvements of organization and coordination. First, the precise public indication of time reduced the urban populations search, match, and waiting time. This enabled people to better plan activities and have more time to do other tasks. In this sense, the clock is an information technology that improves coordination and reduces transaction time, as discussed by Hayek (1945). However, it could also improve the coordinating task itself. The concentration of the market time created thicker markets and could improve the allocation quality between the demand and supply sides. The precise separation of different groups of buyers and sellers allowed towns to create a more powerful market policy. Towns particularly intended to avoid commodity hoarding and speculation. A precise meeting time in markets, town halls, or educational institutions could create better human capital spillover effects within meeting groups. The division of education into single hours allowed for the creation of schedules with alternating easier and more difficult subjects, making the learning experience more productive.[14]

These effects on coordination and organization should be considered in a long-term perspective. If it is true that other types of time measurement devices (e.g., sun and water clocks) can be used for similar purpose of coordination, then the mechanical clock helped to quantify the strikes. According to the historical evidence related to the city of Paris at the beginning of the 14th century collected by Crombie (1961), the mechanical clock allowed for thinking about the time as an abstraction to be quantified during the contemporary life. This effect is also confirmed by studies in physics (Einstein and Infeld (1938)) and neurobiology (Gibbon et al. (1997)), which show that the presence of the mechanical device gradually helps individuals in conforming their personal subjective time with a standard one ("government time").

[13] As remarked by Thompson (1967), during the appearance of the mechanical clocks, it was possible to observe a contemporaneous internalization of time discipline during the working hours as opposed by the rhythm of nature ("task time"). However, this thesis has been recently challenged by recent historiographical research. See Ogle (2015) for a review.

[14] The relevance of time coordination and synchronization in working places has been highlighted from a theoretical point of view by Weiss (1996), while Hamermesh et al. (2008) show that timing altered by daylight, different television schedules and time zones affect temporal working coordination and sleeping time with effects on economic activities.

Furthermore, clocks enabled the coordination and monitoring of production activities (Landes (1983) and Dohrn-van Rossum (1996)). The public clock created an "objective" measurement for the employer and employee or any cooperative group of productive agents. Whereas the use of church clocks and special work clocks as signaling devices had previously been used to determine the starting and ending time of the day for specific working groups, the public mechanical clock could now precisely measure the working time and breaks and enable payment by the hour (and, often, "wage punishment by the hour" when workers did not show up on time) and payment for overtime hours.[15] The public mechanical clock was introduced particularly for simple tasks, for which monitoring and payment by the hour were meaningful. For instance, Landes argues that it must have been particularly useful in the booming textile "industry" of the time. Another well-documented sector was large construction sites, such as those for domes or cathedrals, where many workers had to be coordinated and monitored at the same time (Dohrn-van Rossum (1996)). More differentiated uses of time to precisely define and synchronize work tasks evolved over time.[16] Impressive evidence of the perfection to synchronize work tasks can be found fin the late 17th century law book of the "Crowley Ironworks", the biggest ironwork in Europe at that time, which further illustrates this development (Thompson (1967)).

However, in this case, the use of the clock as a control function did not automatically translate into measures to increase productivity. In a dispute between different guilds in late 14th century France, the public clock was used to coordinate working activities to restrict working time to limit the amount of output produced and create less competition (Fagniez (1877)). Similar evidence can be found for 15th century North Germany, where the restriction of working time ordered by the guilds limited the amount of output and increased the price for products (Wulf (1991)). The implementation of organizational regulations in the form of monitoring and the coordination of the labor force to increase productivity only appeared only over time.

These guild examples show that the use of the clock as a productivity supporting device is related to

[15] To the best of our knowledge, we do not have time series that allow us to test the impact of the public mechanical clocks on wages and, as underlined by Munro (2005), the information whether wages were remunerated either by piecework or based on the time worked is missing. A careful reader might find a potential contradiction with both theoretical and empirical studies in personnel economics, where the switch from hourly wage to a piece rate compensation increases productivity. However, as highlighted by Lazear (1996), this relationship holds if the group of workers paid by piece-rates are a self-selected group that is likely to have a higher productivity than the average worker. Given the historical evidence from Landes (1983), this does not seem the case. He suggested that the introduction of the time signal of the clock did select skilled workers and increased the pressure of unskilled workers, being one of the causes of the historical episode of the *Revolt of Ciompi* (1378-82) in Florence.

[16] A detailed analysis of the construction sector for instance documents changes in regulations in North German cities starting during the late 15th and the 16th century (Wulf (1991)).

the work culture of a society. Thompson (1967) documents how the work culture indeed changed over time. Based on case studies, he shows that after the implementation of the clock, a new perception of work discipline evolved slowly and gradually. Building on Thompson's insights, Glennie and Thrift (1996, 2009) develop this perspective further and argued that along with the implementation and the further development of the clock, a new culture of work coordination, regularity, and repetition evolved. In a different strand of research McClelland (1961) finds empirical evidence for a developing "achieving society" during the early modern times. Härter (2007), using a large sample of German cities and territories, finds an increase in regulations on social orders related to time such as curfew, closing time of taverns, etc., during the early modern times. Further supporting evidence for such a change can be found in the cultural movements of the 16th and 17th centuries (Macey (1979) and Wendorff (1980)). Protestantism of the 16th century identified time as a scarce product that had to be used wisely to achieve moral values and goals during the individuals' worldly life (Engamarre (2009) and Boerner et al. (2019)). Seventeenth century scientists and philosophers, such as Robert Boyle and Thomas Hobbes, used the clock as a metaphor for the functioning of the world and to explain how institutions, such as the state, should work. Finally, this broad penetration can also be reflected in wealthy peoples acquisition of home clocks and watches during the 16th and 17th centuries, which was triggered by the early implementation of public clocks during the 14th and 15th centuries (Cipolla (1967)).

Finally, the invention of the mechanical clock marked the beginning of a new phase of technological innovations where fine mechanics, automation and applied mathematics were combined. Craftsmen were becoming Vitruvian artisans by expanding their knowledge to other fields, early university graduates with craftsmen talents applied their knowledge to creating new machines, and learning-by-doing engineers invented new mechanical tools. This movement has been recently identified as a prephase of the "Scientific Revolution", which took off only during the 17th century (Zilsel (2011), Long (2011), and Zanetti (2017)). It also has been seen as part of a change from a qualitative to a quantitative perception of the world. (Crosby (1997)) Thus this process of technological change created new scale and scope for the further development of science and technology, and as with all the other qualitative findings, it must be analyzed whether it translated into quantitatively measurable numbers in economic growth and development.

2.4 Solar eclipses as instruments

Our econometric analysis can be potentially biased for three reasons, which are a common problem in econometric estimations. First, reverse causality can be a central issue since wealthier cities might have been more likely to adopt a public mechanical clock. Second, although we used several regressors that have been used in studies that analyzed the long-run growth of cities, our estimated equation can suffer misspecification. Finally, our historical data might be affected by potential measurement errors. In our empirical analysis, we will use an instrument based on solar eclipses.[17]

In this section, we aim to support this claim by historical narratives and stylized facts. Further quantitative evidence will be provided later. The use of solar eclipses as an instrument for the implementation of public mechanical clocks requires a more detailed two-step analysis. In the first step, we present the link between the appearance of solar eclipses, the curiosity of the western society to understand these phenomena, and the creation of astronomic instruments to measure and understand these events. In the second step, we describe the connection between astronomic instruments and the first public mechanical clocks.

The observation and documentation of the course of the celestial bodies and specific astronomic events date back to ancient times (Lindsay (1858) and Steele (2000)). Solar eclipses have elicited a special fascination. They could be observed by everyone, and due to their rare appearance, they were perceived as sudden, irregular, and often supernatural events. This was, in particular, perceived this way by the European medieval society where in contrast with the Arab and Chinese societies, hardly any recently compiled astronomic knowledge existed (the ancient Greek knowledge was almost forgotten).[18] These celestial movements created much curiosity and speculation, and left room for interpretation in European societies. Whereas there was an interest in understanding, learning, and catching up on astronomic knowledge from the Arabic world (Chabas and Goldstein (2012)), the movement and constellation of the celestial bodies was very much understood as God's work. Therefore to understand and predict the future constellation of the stars meant to be closer to God's plan and revelation (Borst (1989)). Coincidental political and religious events during solar eclipses supported such causal reasoning further. For instance, in one of the Gospels, the evangelist Luke

[17] In Section 6, we consider distance from the first adopters as an alternative instrument.

[18] Stephenson (1997) reports a large set of sources that document the different perception of solar eclipses by varies societies.

reports a total solar eclipse during the crucifixion of Jesus. In other examples the death of the son of Mohamed in 632 and the death of the emperor Louis and the Treaty of Verdun in 840 coincided with solar eclipses. In addition, beyond this connection between astronomy and religiosity, the field of astrology also developed (which was not clearly separated from astronomy), in which the prediction and understanding of the constellation of the stars was related to personal future, destiny and the fortune of whole societies (Blake (2014)).[19] For instance the appearance of a solar eclipse exactly 1000 years after the crucifixion of Jesus created speculations about the end of the world (Borst (1989)). Furthermore, there is also ample evidence of the existence of astronomical and astrological advisors at the European royal courts and aristocratic houses starting during the 12th and 13th century (Mentgen (2005) and Deimann and Juste (2015)). Again, European rulers were particularly receptive to the advice. For example, Guido Bonatti who was an Italian mathematician, astronomer and astrologer served Frederik II during the second half of the 13th century. Bonatti advised Frederik II on many political decisions (for instance, the optimal constellation for going to war) and became one of the most important astrologers and public figures of the time.

The study of these heavenly bodies and astronomic events required the development and the application of various instruments. In particular, so-called astrolabes were developed, which date back to ancient times and were transmitted from the Arabs to medieval Europe (Turner (1911)). An astrolabe was able to measure and simulate astronomic constellations and to measure time in equinoctial hours.[20] Astrolabes became essential instruments for astronomers and astrologers to measure constellations of heavenly bodies. The use of the time function was in particularly important in European astrolabes (McCluskey (2000)). Furthermore, also sun and water clocks were also used to measure astronomic activities; however, they were not as versatile and easy to handle as astrolabes. In Europe, water clocks can be observed in particular in medieval monasteries, where they were also used to study astronomy. The construction of several very advanced astronomic water clocks to study astronomy can be documented in the medieval Islamic world and in medieval China (Cipolla (1967) and al Jazari (1973)) The connection between astronomic events and the development of machines measuring astronomic movement is not an exclusively medieval phenomena. Looking at some arche-

[19] The European astrological tradition was very much based on Islamic astrology which had its peak much earlier on. However the main books had only been translated by the 12th century into Latin.

[20] The places where these astrolabes were found in Europe (King (2011)) seem to overlap with areas where solar eclipses frequently appeared. However, due to the fragmented nature of the source material, further quantification is not possible

ological discoveries, we can find some suggestive links between astronomic events and prototypical machines for measuring time.[21]

Therefore, we can establish a link between the observation of astronomic events and the creation of instruments and basic machines to measure these events. The use of solar eclipses not only appears to be a strong motivation for the development of intellectual curiosity and astronomic instruments but also enables us to separate Europe into both areas with and without eclipses and consequently areas with stronger or weaker motivation to study and understand astronomy.

The second link is between astronomic instruments and the development of public mechanical clocks. Price (1955) and White (1978) stress that mechanical clocks are not originated by previous forms of clocks but by *planetaria* and geared astrolabes. Dohrn-van Rossum (1996) states that medieval scholars were interested only in the development of machines that were related to astronomy. Cipolla takes the clock as a prime example of such a machine. Whereas the precise sequence and evolution from earlier clocks and astronomic instruments to the creation of public mechanical clock have been widely debated, there are no doubts that a clear correlation can be established, which was outlined in Section 2.1. Consequently, we can use the appearance of solar eclipses through the curiosity, invention and application of related astronomic machines as an instrument for the implementation of public mechanical clocks. More precisely, we consider regions and cities where solar eclipses appeared as places with a higher likelihood of building clocks.[22]

[21] As matter of example, juxtaposing the number of total solar eclipses during the ancient times with the location of the astrological heritage provided by the United Nations Educational Scientific and Cultural Organization (UNESCO) and available at `https://www3.astronomicalheritage.net/`, we can observe several cases where ancient and more recent astronomical sites are located next to intense solar eclipse activities. Keeping in mind that this sample is not representative, we would like to refer to the examples of Stonehenge (Hawkings (1988)), the Stone Circle of Odry in Poland (Sadowski et al. (1993)), and the Navajo star ceiling in the US (Williamson (1984)). Two case studies are particularly striking. The first one is related to the archeological site located at Deir el-Bahri in Egypt. According to the archeological interpretation of the discoveries of the Tomb of Senenmut at Western Thebes (Neugebauer and Parker (1988)), and dated 1470 B.C., the ceiling of the heritage depicts one of the oldest representation of the celestial firmament, which was inspired by the direct vision of the celestial movements and very likely influenced by two total solar eclipses during the years 1522 B.C. and 1477 B.C., respectively. In addition, the problem of measuring the astronomical time justifies the presence in the tomb of a monumental guideline for the construction of a water clock (*clepsydra*), which would be introduced later by the Egyptians in the Roman Empire (Sloley (1931)). The second example is related instead to the so-called *Antikythera* mechanism, dated to 205 BC and discovered from a shipwreck on the omonimous Greek island of Antikythera. Defined by Price (1959) as an "ancient Greek computer", it is a primordial clocklike mechanism for calculating the motion of stars and planets and for predicting eclipses during the eclipse cycle of 223 lunar months.

[22] The reader might wonder why we use cities and regions rather than the location of monasteries as the crucial geographical points and connections. First, we are interested in the implementation of public mechanical clocks in cities and their related growth path. Second, most medieval cities that we study had at least one monastery inside their town walls and all of them had one in their immediate neighborhood. Therefore, the use of cities as geographical loci of potential human capital accumulation and adopters of the clock can be justified.

To conclude this descriptive two-stage analysis we give some narrative historical case studies of various towns that were covered before the introduction of clocks by several solar eclipses (as defined later on), had links to astronomy and were among the first adopters of the public mechanical clock: In Mechelen, a Flemish city, the astronomer and philosopher Henry Bate of Mechelen both elaborated tables for predicting eclipses (the so-called *Tabulae Mechlinenses*) and claimed to have built an astrolabe containing a time component at the end of the 13th century (White (1978) and Zanetti (2017)), and one of the first public mechanical clocks can be found, which also had an astronomical component. Another example is the city of Erfurt, where historical sources document the existence of astronomical and astrological experts (which must have been equipped with astrolabes) during the 13th century (Mentgen (2005)). Indeed Erfurt was also one of the first towns in Germany with a public mechanical clock. Another interesting case is Perpignan (the seat of the King of Aragon) where a strong astronomic interest and a collection of astrolabes by King Pedro IV preceded the building of the first public clock on the Iberian Peninsula. It is also documented that the King had several astronomers and specialized metal workers at the court who developed and maintained his scientific instruments (Beeson (1982) and Perez-Alvarez (2013)). Finally, the city of Padua has one of the earliest and still existing astronomical clocks. Padua became one of the most important centers for astrology in Europe starting during the late 13th and early 14th century, for instance, with Pietro D'Abano, who was a professor at Padua University and an expert in astrology and astronomy with in-depth knowledge of the astrolabe (e.g, Canova (2011)).

3 Data

This section contains an overview of the city- and country-level variables considered in the empirical analysis.[23] We determine the presence of and the year of adoption of public mechanical clocks during the period of our analysis mainly from four different sources: Bilfinger (1892), who analyzes the introduction of city clocks in France, Germany, England and Italy; Ungerer (1931), who provides a list and description of mechanical clocks in Europe; Dohrn-van Rossum (1996), who historically describes the adoption process, and Glennie and Thrift (2009), who concentrate their attention on the use of time in England. This initial dataset is integrated with an additional and nonpublished

[23] Table A1 in Appendix A contains the descriptive statistics of these variables.

list provided to us by Dohrn-van Rossum with other information from other sources (Cipolla (1967) and Landes (1983)). In addition, when possible, we confirm the date of adoption with the original historical sources. Our final list contains 182 clocks adopted between 1283, the date of adoption of the first mechanical clock in Dunstable, England, and 1450, when it is assumed that the period of yearly adoption concluded.[24] Table 1 displays the aggregate number of clocks adopted, the number of cities with more than 5,000 inhabitants in 1400, and the percentage of adoption, which was computed as the ratio of the first two columns, at country level.[25] We can observe that the adoption rate has an average of 20%, which covers both areas with low diffusion (e.g., Spain with 3%) and areas with more intense adoption (Switzerland with 90%).

Table 1: The Diffusion of the Mechanical Clock in Europe before 1450.

Country	**Cities adopting the clock**	**Cities available in Bairoch in 1400**	**Percentage of adoption**
Austria	1	8	13
Belgium	14	33	42
Czechia	1	5	20
France	27	74	36
Germany	45	301	15
Italy	39	101	39
Malta	1	1	100
Netherlands	13	35	37
Poland	5	19	26
Spain	8	262	3
Sweden	8	18	44
Switzerland	10	11	90
Ukraine	1	2	50
United Kingdom	9	60	20
Total (all sample)	**182**	**931**	**20**

Source: Authors' calculation based on the clock's dataset. Population data drawn from Bairoch et al. (1988).

In addition, we collect population data from Bairoch et al. (1988) which allows us to consider the population in all cities with more than 5,000 inhabitants for ten periods (i.e., 1000, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, and 1850). Following DeLong and Shleifer (1993) and Acemoglu et al. (2005a), we assume that population is a good proxy for urban income because data on urban GDP are not available before 1500.[26]

[24]In addition, we build a more extended list to 1600 to compute the penetration rate at the country level.
[25]In Section 7, we compute the penetration rate weighted by the population.
[26]Unfortunately, we don't have population data more frequent than 100 years which would allow us to perform some

Furthermore, we construct a measure of productivity at a more aggregated level by considering GDP per capital measured in 1990 PPP International Dollars and the total population of 10 countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Sweden, Switzerland, and United Kingdom) from Maddison (2007) and McEvedy and Jones (1978), respectively.

Data on the geographical positions (longitude and latitude) of cities, the locations of both big and small rivers and the presence of cities on sea coasts, and altitude are derived from McEvedy and Jones (1978), Nuessli (2011), Nunn and Qian (2011) and historical and geographical atlases. Data on Atlantic and Mediterranean ports are taken from Acemoglu et al. (2005b). We construct our own data on ports related to the Baltic area based on different geographical and historical atlases. We also collected data on geographical amenities. More specifically, we consider the potential agricultural output, which can be measured either considering the crop suitability derived by the Food and Agriculture Organization's Global Agro-Ecological Zone (FAO's GAEZ) 2002 database[27] or, alternatively, by the data constructed by Galor and Özak (2016),[28] which provide the maximum amount of potential calories attainable from the cultivation before and after 1500. This will allow us to control for potential changes due to the Columbian Exchanges. In addition, from Nunn and Puga (2011) we borrow other indicators that can summarize the natural amenities of the cities, such as the potato crop suitability, the total amount of suitable land, a measure of ruggedness, and the city elevation.

Finally, to test the potential effects of the early adoption of public mechanical clocks on cultural values, we collect country-level data on long-term orientation and the pace of life (i.e., walking speed, postal speed, and clock accuracy) from Hofstede et al. (2010) and Levine and Norenzayan (1999). In addition, we are inspired by the empirical exercise in Galor and Özak (2016), and we extract a variable on long-term orientation and the individual characteristics from the European Social Survey (ESS).[29] In Section 7 we will provide a more detailed explanation of the variables belonging to the ESS.

city case studies. We do not have precise information on population before 1000 and, thus, we use the five-folded classification of city size provided by Nuessli (2011).

[27]This dataset, which can be downloaded at the following link http://www.fao.org/nr/gaez/en/, provides an index on average potential output diving the world territory in cells of approximately 56×56 kilometers. Nunn and Qian (2011) provide a detail description of the data.

[28]The dataset can be download at the following link https://ozak.github.io/Caloric-Suitability-Index/

[29]The answers are derived from the question asked "*Do you generally plan for your future or do you just take each day as it comes?*" and it spans between the value of 0, i.e., when individuals have the lowest level of orientation, and 100, i.e., when the person interviewed has a long-term orientation.

3.1 Total solar eclipses as instrumental variable

The data on solar eclipses are taken from the National Aeronautics and Space Administration (NASA) website.[30] We consider both total and annular solar eclipses: during a total solar eclipse, the sun is completely obscured by the moon, while during annular eclipses, the moon appears smaller than the sun. Table 2 shows the entire list of eclipses that have covered the European area from 800 to 1200. We consider the land territory in Europe[31] (reported in bold in the table) following two criteria, which can be rationalized based on the intensity of the perception of the eclipses. First, the geographical area should be overlapped by the umbral pattern of at least two eclipses within 100 years during the period 800-1283, the latter of which is the year of the first adoption of the mechanical clock.[32] Second, the eclipse should last more than one minute. This means that we exclude the eclipses in 1033 and 1039. Figure 4 displays the umbral pattern of both total and annular eclipses and the main town and city centers during the 9th, 10th, 11th, 12th, and 13th (before the introduction of the first clock in 1283) centuries. The yellow color highlights the areas where the eclipses overlap. In addition, Figure 5 compares the abovementioned areas in Europe with more than one total or annular solar eclipse, the main population areas with (in black) and without (in gray) mechanical clocks. In addition, in this figure we can see a relationship between the astronomical events and the adoption of the new technology. In addition, we observe that the earlier is the first eclipse covering the city, the earlier the adoption of the mechanical clock.[33] As an additional instrument, we consider the distance from the nearest very first innovators, i.e., cities adopting the mechanical clock before 1350. These measures are computed using GIS data from Nuessli (2011) using the nearest neighbor analysis technique. The maps on the upper part of Appendix A display the cities that are considered the first innovators.

[30] Espenak (2015), http://eclipse.gsfc.nasa.gov/eclipse.html. The data are downloaded from Xavier M. Jubier's website: http://xjubier.free.fr.

[31] Unfortunately, for the period 800-1000 we do not have detailed data on population level from Bairoch et al. (1988). We consider instead the already mentioned classification contained in Nuessli (2011), who ranks the populated centers in five different categories according to their importance. We considered the centers enlisted in the two most important categories.

[32] We do not observe any relevant overlapping eclipse activities during the period of 600-800.

[33] We compute a positive correlation of 0.13.

Table 2: Total and Annular Eclipses during the Medieval Period in Europe.

Date	Type	Duration in Seconds
May 5th, 840	**Total**	**346**
March 3rd, 852	**Annular**	**313**
October 29th, 878	**Total**	**110**
August 8th, 891	**Annular**	**342**
July 19th, 939	**Total**	**342**
May 17th, 961	**Annular**	**114**
December 22nd, 968	**Total**	**148**
October 21st, 990	Annular	489
January 24th, 1023	Total	180
June 29th, 1033	Annular	0.4
August 22nd, 1039	Annular	0.1
April 19th, 1064	Annular	238
February 16th, 1086	**Total**	**288**
September 23rd, 1093	Annular	123
December 25th, 1098	**Annular**	**533**
May 31st, 1109	Annular	311
August 11th, 1124	Total	199
August 2nd, 1133	Total	278
October 26th, 1147	Annular	251
January 26th, 1153	**Annular**	**413**
September 13th, 1178	Total	238
May 1st, 1185	Total	310
September 4th, 1187	Total	245
June 23rd, 1191	Annular	268
November 27th, 1201	Annular	376
February 28th, 1207	**Annular**	**272**
June 3rd, 1239	Total	318
October 6th, 1241	**Total**	**218**

Source: Espenak (2015). The eclipses marked in bold are the ones selected for constructing our instruments. Section 4 contains the criteria for our selections.

Figure 4: Total and Annular Solar Eclipses during IX, X, XI and XII century. Source: Authors' calculation using Nuessli (2011)'s and Espenak (2015)'s data.

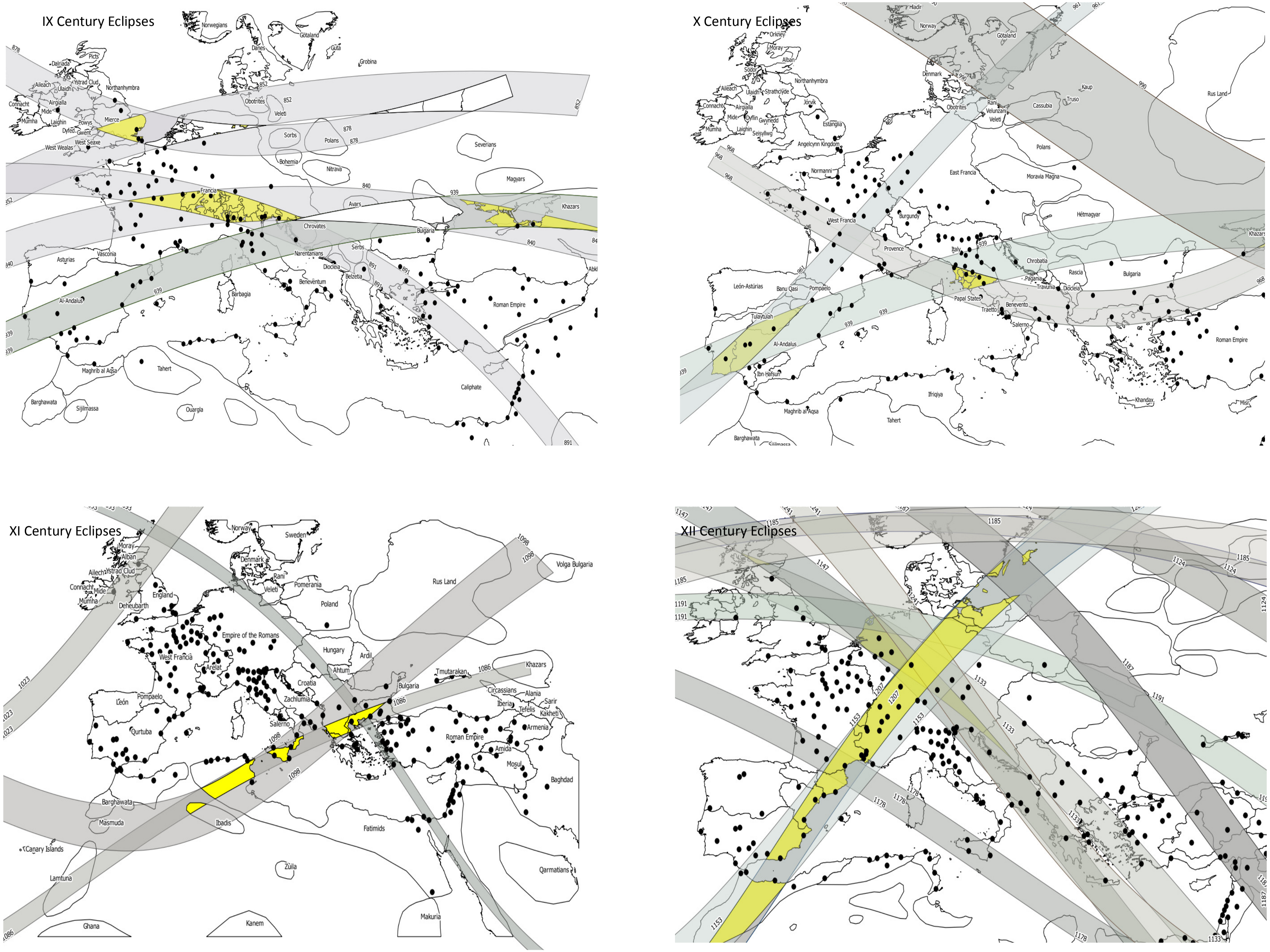
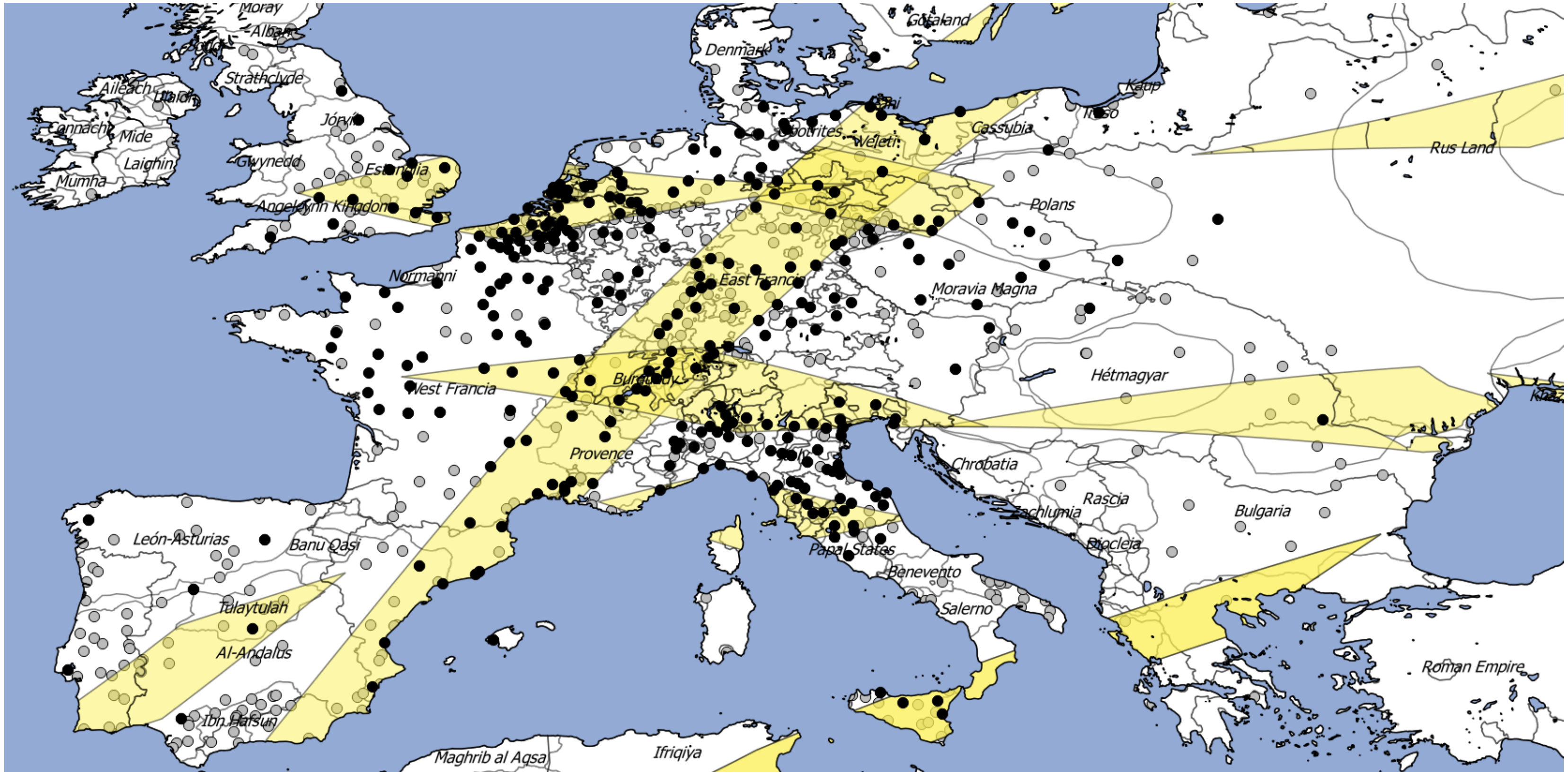


Figure 5: Area in Europe with more than one total or annular solar eclipse. Source: Authors' calculation using Nuessli (2011)'s and Espenak (2015)'s data.



4 Empirical strategy

We start our empirical analysis by considering a generalized differences-in-differences (DiD, henceforth) of the following form:

$$\ln POP_{it} = \gamma_i + \delta_t + \beta_1 CLOCK_{it} \cdot Post_{it}$$

$$+ \beta_2 CLOCK_i \cdot Post_{it} \cdot Trend_{it} + \alpha X_{it} + \epsilon_{it} \quad (1)$$

where, for city i and year t, γ_i and δ_t are city and year fixed effects (i.e., 1000, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, and 1850), respectively. POP_{it} represents city size in terms of population, $CLOCK$ is a dummy that takes a value equal to 1 if the city has adopted a mechanical clock before 1450, and 0 otherwise, $Post$ is a dummy that takes a value equal to 1 if the city has adopted the mechanical clock in year t, and 0 otherwise, $Trend$ is the difference between the year of adoption and t, X_{it} is a set of controls, and ϵ_{it} is the error term. As in the specification proposed by Cantoni (2015), this equation allows us to consider both the average of the effect of the adoption of the public mechanical clock in city size (β_1) and potential city-specific trend (β_2), which catches the individual technological level. As an additional and more flexible DiD specification, we also test the following equation:[34]

$$\ln POP_{it} = \gamma_i + \delta_t + \sum_{\tau \in T} \beta_\tau CLOCK_i \cdot I_\tau + \alpha X_{it} + \epsilon_{it} \quad (2)$$

with T covering the years that are available. The β_τ before and after the adoption of the mechanical clock will provide information on potential anticipatory and post treatment effects, respectively. We generally take as baseline the year 1000: this means that the size of the coefficients β will display the differences with respect to the year considered and thus should be interpreted in terms of significance and dynamics. Table 3 shows the results of the OLS estimation[35] of equations (1) (first part) and (2), respectively, considering different set of variables, which have been commonly used in the literature, and time and city fixed effect with robust standard error. More precisely, in column (1), we control for geographical coordinates (longitude and latitude), and then, we consider additional regressors such

[34]Equation 2 allows us to test Granger causality. See Granger (1969) and Angrist and Pischke (2008).

[35]We prefer an OLS instead of a fixed effect estimation since our panel is unbalanced and, as shown by Fernandez et al. (2016), the OLS technique provides more precise estimates.

as whether cities are Atlantic ports for controlling for potential effects of the Columbian Exchange (column (2)), calories (3), and other geographical variables[36] described in Section 3 (column (4)). In addition, in column (5) we introduce the level of the population during 1200 which allows to control for potential barrier costs in building the mechanical clocks.[37] The results reported in the first part of Table 3 are robust over the different specifications: given the coefficients of the different sets of regressions and computing the marginal effects, we can quantify a positive and significant effect of the introduction of the mechanical clock on a time span of more than two centuries. In this set of regressions, the standard errors that clustered on time-invariant countries may be biased due to potential temporal autocorrelations. We also attempt to adjust the standard errors following the methodology introduced by Conley (1999) and obtain very similar values.[38] Furthermore, consistently with the results represented in Figure 3, the estimation results of equation (2) display no effects in the 13th century, while there is a positive impact between 1300 and 1700.

[36]More precisely, potato crop suitability, amount of land suitable in the Old World, the amount of ruggedness, and elevation.

[37]In addition, this controls for the dynamics related to the mortality shock of the Black Death, which might lead to the increase to higher income per capita and thus a faster transition to the steady-state.

[38]More precisely, an estimate for cross sectional OLS corrected for spatial dependence of the specification of column (4) of Table 3 (first part) will give an estimated coefficient for $CLOCK \cdot Post$ equal to 0.22 and a corrected standard error of 0.09.

Table 3: OLS Regressions

Dependent variable: ln POP	(1)	(2)	(3)	(4)	(5)
1. Difference-in-difference					
$CLOCK$	1.72***	1.71***	1.46***	1.58***	1.16***
	(0.55)	(0.55)	(0.49)	(0.41)	(0.41)
$CLOCK \cdot Post \cdot Trend$	0.11***	0.11***	0.09***	0.10***	0.07**
	(0.04)	(0.04)	(0.03)	(0.03)	(0.03)
p-value for joint significance $CLOCK$	0.01	0.01	0.02	0.00	0.02
Adjusted R^2	0.66	0.66	0.66	0.69	0.70
2. Flexible Difference-in-difference					
$CLOCK \cdot$					
$YEAR = 1200$	0.29	0.29	0.25	0.13	
	(0.28)	(0.28)	(0.26)	(0.27)	
$YEAR = 1300$	0.83***	0.83***	0.75***	0.66***	0.45***
	(0.22)	(0.22)	(0.21)	(0.20)	(0.12)
$YEAR = 1400$	0.80***	0.80***	0.69**	0.60**	0.44***
	(0.28)	(0.28)	(0.28)	(0.26)	(0.14)
$YEAR = 1500$	0.61**	0.60**	0.56**	0.45**	0.32***
	(0.23)	(0.23)	(0.21)	(0.20)	(0.11)
$YEAR = 1600$	0.60**	0.60**	0.56**	0.48**	0.37***
	(0.23)	(0.23)	(0.22)	(0.22)	(0.13)
$YEAR = 1700$	0.72**	0.73**	0.74**	0.60**	0.46***
	(0.29)	(0.29)	(0.27)	(0.25)	(0.14)
$YEAR = 1750$	0.49*	0.49*	0.48*	0.36	0.26**
	(0.26)	(0.26)	(0.24)	(0.23)	(0.11)
$YEAR = 1800$	0.36	0.37	0.36	0.24	0.15
	(0.27)	(0.27)	(0.26)	(0.25)	(0.11)
$YEAR = 1850$	0.26	0.26	0.26	0.13	0.08
	(0.29)	(0.29)	(0.28)	(0.26)	(0.12)
p-value for joint significance $CLOCK$	0.00	0.00	0.00	0.00	0.00
Adjusted R^2	0.66	0.66	0.67	0.68	0.69
Geographical coordinates	Y	Y	Y	Y	Y
Atlantic harbors	N	Y	Y	Y	Y
Calories	N	N	Y	Y	Y
Geographical variables	N	N	N	Y	Y
Population at 1200	N	N	N	N	Y
Number of observations	9,319				9,208
Number of clusters			41		

City and year fixed effects included in all regressions. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

As described in the previous section, the OLS results displayed in Table 3 might be affected by several biases. First, reverse causality can be problematic. Endogeneity issues of the variable $CLOCK$ on the dependent variable can arise because a city's growth may drive the early adoption of the mechanical clock. In addition, equations (1) and (2) can be misspecified: institutional and other city characteristics (e.g., cities' policies and institutional quality), which are not observable, might also play a role. Finally, the historical variables we use in the specification might be affected by measurement errors. For these reasons, we consider a two-stage-least-squares model based on two different equations, where the first stage considers the relationship between the adoption of the mechanical clock and the eclipses:

$$CLOCK_i \cdot I_t = \rho_c + \gamma_t + \sum_{t \in T} \nu_t Eclipse_i \cdot I_t + \sum_{t \in T} \alpha_\tau X_i \cdot I_t + \zeta_i \quad (3)$$

In this equation ρ_c and γ_t represents the city and time fixed effects, respectively, while the second stage is identical to equations (1) and (2) except for having the prediction of (3), i.e., $\widehat{CLOCK_i} \cdot I_t$, instead of the dummy generated by the interaction $CLOCK_i \cdot I_t$. *Eclipse* is the number of total solar eclipses that occur in the city in a time-span of a century. Looking at the first stage, we verify that the instrument is not weak considering different sets of logit estimates.[39] Table 4 shows a significant and positive relationship between the adoption of the public mechanical clock and the number of eclipses independently on the specification we consider. Furthermore, Table A2 in the Appendix shows that the hypothesis of weakness is once again rejected after having analyzed the multiple partial F-test statistics for each endogenous regressors.[40] Finally, we assess whether eclipses are tested to be exogenous using the same type of strategy and estimation suggested by Rubin (2014): as reported in Table A3 in the Appendix; after controlling for different sets of regressors, we find that eclipses did not explain institutional and geographical variable, with the only exception of that of being a Hanseatic center.

Table 5 displays the second stage of the IV regression. The results are similar to those obtained by the OLS estimates: while in the first part of the table, the basic instrumented DiD shows a positive and significant effect of the public mechanical clock on the level of population with marginal

[39] The use of the logistic distribution is motivated by the best representation of the S-shape curve of adoption, as in Geroski (2000). In separate regressions we also consider the variable *Eclipse* as a dummy and we also estimate linear probability models. In both cases, we obtain very similar results for the relationship between the total solar eclipses and the adoption of the mechanical clock.

[40] To avoid estimation problems with overidentification, we consider for our set of time dummies interacted with clock we consider all the time dummies interacted for *Eclipses* except for the year 1200.

Table 4: Logit regressions

	Dependent variable: *CLOCK*				
	(1)	(2)	(3)	(4)	(5)
Eclipse	0.72***	0.73***	0.96***	0.99***	1.10***
	(0.22)	(0.22)	(0.21)	(0.23)	(0.26)
Longitude	0.01	0.01	-0.05***	-0.05***	-0.05**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Latitude	0.03	0.04	0.13***	0.13***	0.15***
	(0.03)	(0.03)	(0.02)	(0.04)	(0.04)
Atlantic		-0.47	-0.31	-0.22	-0.34
		(0.36)	(0.30)	(0.32)	(0.41)
Calories			0.37***	0.32***	0.30***
			(0.00)	(0.00)	(0.00)
Potato				0.06	0.06
				(0.08)	(0.09)
Land suitability				0.22	0.19
				(0.19)	(0.20)
Ruggedness				0.07	-0.16
				(0.51)	(0.61)
Elevation				0.12	0.29
				(0.39)	(0.43)
Population 1200					0.20***
					(0.02)
Constant	-2.76**	-2.78**	-11.29***	-14.39***	-15.64***
	(1.39)	(1.40)	(1.09)	(3.81)	(3.81)
Pseudo R^2	0.03	0.02	0.11	0.12	0.20
Number of observations			684		

City and year fixed effects included in all regressions. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

effects comparable to the ones obtained by the OLS, in the second part we still observe increasing positive and significant effects of the mechanical clock on population dynamics between 1500 and 1700, which confirms the delay of the benefits of the technological adoption. These dynamics can be better visualized in Figure 6, which graphically compares the results of column (4) obtained in Tables 3 and 5, respectively.

Table 5: IV Regressions

Dependent variable: $\ln POP$	(1)	(2)	(3)	(4)	(5)
1. Difference-in-difference					
$CLOCK$	6.99**	7.03**	6.88***	5.70**	5.16*
	(2.90)	(2.96)	(2.20)	(2.68)	(2.70)
$CLOCK \cdot Post \cdot Trend$	0.35**	0.36**	0.36***	0.30**	0.28*
	(0.16)	(0.17)	(0.12)	(0.15)	(0.15)
p-value for joint significance $CLOCK$	0.03	0.04	0.01	0.07	0.15
2. Flexible Difference-in-difference					
$CLOCK\cdot$					
$YEAR = 1200$	1.92	1.92	1.95	0.97	
	(1.66)	(1.66)	(1.69)	(1.17)	
$YEAR = 1300$	1.28	1.29	1.55	1.46*	0.46
	(2.00)	(2.00)	(1.80)	(0.86)	(0.49)
$YEAR = 1400$	0.90	0.91	1.42	1.31	0.43
	(2.16)	(2.16)	(1.76)	(0.87)	(0.58)
$YEAR = 1500$	2.47	2.49	2.41	2.15***	1.09**
	(1.56)	(1.56)	(1.49)	(0.72)	(0.56)
$YEAR = 1600$	2.56*	2.56*	2.33	2.31***	1.15*
	(1.54)	(1.54)	(1.50)	(0.83)	(0.67)
$YEAR = 1700$	2.92**	2.90**	2.45*	2.22***	0.72
	(1.27)	(1.27)	(1.45)	(0.73)	(0.60)
$YEAR = 1750$	1.50	1.51	1.50	1.32*	0.36
	(1.65)	(1.65)	(1.57)	(0.80)	(0.59)
$YEAR = 1800$	1.30	1.31	1.28	1.13	0.26
	(1.59)	(1.59)	(1.56)	(0.77)	(0.56)
$YEAR = 1850$	0.86	0.86	0.90	0.87	-0.05
	(1.70)	(1.70)	(1.67)	(0.95)	(0.55)
p-value for joint significance $CLOCK$	0.01	0.01	0.00	0.00	0.04
Geographical coordinates	Y	Y	Y	Y	Y
Atlantic harbors	N	Y	Y	Y	Y
Calories	N	N	Y	Y	Y
Geographical variables	N	N	N	Y	Y
Population at 1200	N	N	N	N	Y
Number of observations		9,319			8,572
Number of clusters			41		

Instruments considered: number of total solar eclipses in a time-span of a century interacted by year. City and year fixed effects included in all regressions. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively. Exogenous regressors are partialled out.

Figure 6: The effects of *CLOCK* on population. OLS and IV coefficients of the flexible DiD.

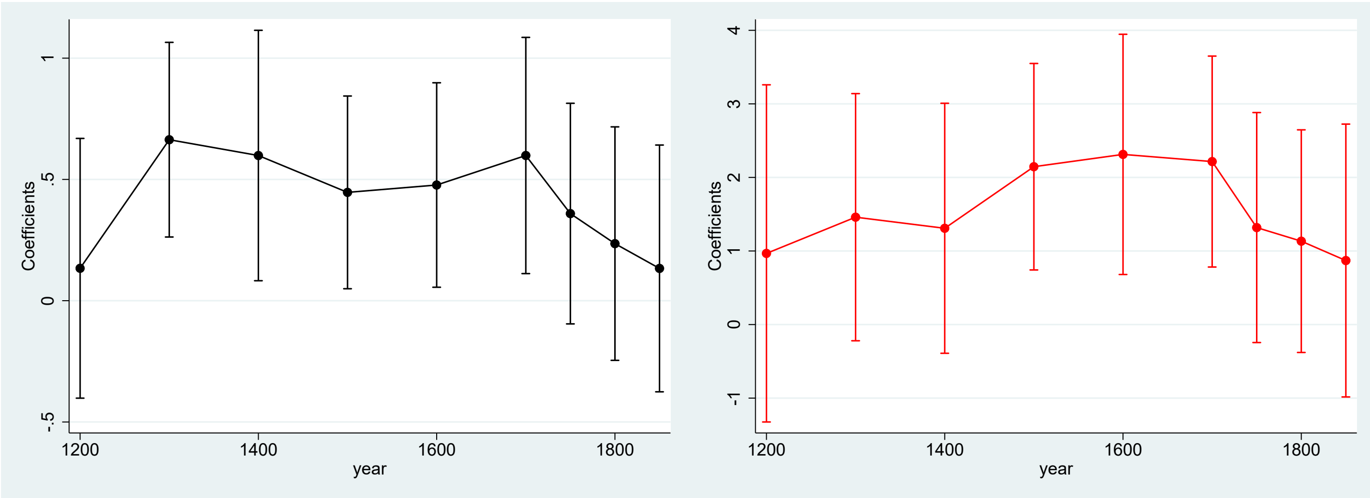


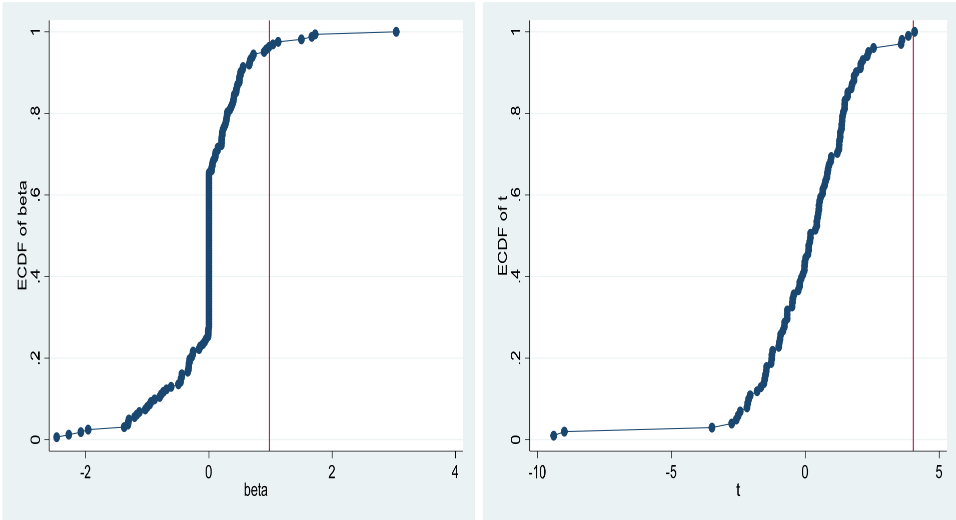
Figure 6 displays the coefficients of specification (4) of the flexible DiD reported in column (4) of Tables 3 (on the left) and 5 (on the right). Confidence intervals at 95% reported.

Our instrument is based on the assumption that the eclipses had a direct effect on the adoption of the mechanical clock. We test this hypothesis by considering a set of placebo tests that exploit both the past and the future trajectories of total and annular eclipses. The data provided by Espenak (2015) allow us to track these astronomical events for a period before the contribution of our instrument, i.e., from 2000 B.C. to 800 A.D. In addition, we collect information over the period 1450 to 3000 A.D. We construct the instruments while summing up the number overlapping eclipses for cities in intervals of 100 years.[41] We move the sum each year, which allows us to construct 168 different placebos. We rerun the regressions by substituting one of the placebos each time. Similar to the graphical representation of placebos in Madestam et al. (2013), the left hand side of Figure 8 shows the empirical cumulative distribution function of the different coefficients of *Eclipse* from the 168 different placebos of the logit regression that we use as a first stage.[42] On the right-hand side we report the comparison of the respective $z-$statistics. The figure suggests that not only are the actual estimates (represented by the red line) is an outlier with respect to the entire distribution (only 3.57% of the coefficients are higher) but also that only 5.95% of the coefficients are significantly different (99%) from zero, which provides additional support for the positive causal relationship between the frequencies of the actual eclipses and the adoption of the public mechanical clock.

[41] To be restrictive in our exercise, we consider all the cities available in the dataset, independently on the appearance in particular years in the Bairoch et al. (1988) dataset.

[42] More precisely, we consider the specification reported in column (5) of Table 4 compared to the actual estimates.

Figure 7: Placebo test based on 168 historical and future total solar eclipses



On the left we compare the effective estimates of the logit regression reported in Table 4 (red line) with the empirical cumulative distribution function (ECDF) obtained by 168 placebos. On the right the figure displays the effective $z-$statistics with the ECDF of the placebos.

5 Additional robustness checks

In this section we are going to test the robustness of the results reported in our OLS and IV estimations in several ways. First, we look at the potential effect of another important technology introduced at the end of the Middle Ages, i.e., the printing press. Second, we propose a different instrument. Third we test the relationship between the adoption of the public mechanical clock and the population exploiting a propensity score matching technique. Fourth, we test whether our results are affected by particular subsets of the dataset considered. Finally, we exploit the time of adoption as additional information for our estimation.

Considering the first issue, we study the potential relationship between the mechanical clock and a more recent innovation, i.e., the printing press, since recent contributions have underlined the relevance of this technology on both economic growth (Dittmar (2011)) and the adoption of Protestantism (Rubin (2014)).[43] To have results comparable to the work of Dittmar (2011), we consider the following econometric specification, which is inspired by the classical equation formula that was derived by

[43] Boerner et al. (2019) study the effect of both mechanical clocks and the printing press on the choice of religious beliefs and, in particular, Calvinism.

Mankiw et al. (1992), where economic growth is explained by a set of variables that are related to the input of production and human capital and the initial economic condition of the period studied (Barro (1991)):

$$\Delta \ln POP_{itx} = \beta_0 + \beta_1 CLOCK_i + \beta_2 Press_i + \beta_3 CLOCK_i \cdot Press_i + \beta_4 X_{it} + \beta_5 \ln POP_{i0} + v_{it} \quad (4)$$

where for each city i and time $t = 1400, 1500, 1600, 1700, 1800$ and $x = t-100, t-200, t-300, t-400$, $\Delta POP_{it-x} = \ln\left(\frac{POP_{it}}{POP_{ix}}\right)$, $\ln Pop_{i0}$ is the initial level of population, and X is a set of control variables that were described in the previous section. In addition, we include the two dummies of the technological innovations ($CLOCK$ and $Press$) and their interaction. The OLS estimates of equation (4) are reported in Table 6. To study the long-run effects, we consider six different intervals of time: 1200-1300, 1300-1400, 1400-1500, 1500-1600, 1500-1700, and 1500-1800. While these estimates display very similar results to the work of Dittmar (2011), we again find a positive effect of the mechanical clock on population growth during the period 1500-1700. A further empirical discussion of the relationship between both technologies can be found in Boerner et al. (2019):

Table 6: OLS Regressions

	Dependent variable: $\Delta \ln POP$				
	(1)	(2)	(3)	(4)	(5)
Periods:	1300 – 1400	1400 – 1500	1500 – 1600	1500 – 1700	1500 – 1800
$CLOCK$	0.10	0.03	0.02	0.17**	0.08
	(0.08)	(0.10)	(0.05)	(0.06)	(0.08)
$Press$			0.19**	0.22**	0.27**
			(0.07)	(0.08)	(0.11)
$CLOCK \cdot Press$			0.02	-0.01	0.08
			(0.06)	(0.10)	(0.11)
Adjusted R^2	0.02	0.17	0.16	0.22	0.31
N. of observations	277	228	489	511	609

Controls considered in column (4) of Table 3 included in all regressions. Standard errors are robust and clustered by country. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

As an additional robustness check, we also consider as an alternative instrument the distance from the very first adopters.[44] As previously outlined, the adoption of mechanical clocks occurred in a few

[44] The distance from a knowledge source has been already examined in relation to education and labor economics

cities in a first wave in different regions in Europe. Then, diffusion in these and neighboring regions can be observed. The diffusion pattern can be explained by the fact that only a few experts had clockmaking skills. These clock makers traveled from city to city to sell their expertise by building mechanical clocks, and their expertise was shared slowly (Cipolla (1967), Landes (1983) and Dohrn-van Rossum (1996)). Thus, the likelihood of the implementation of a clock in a town depended on the distance from one of the first adopters. Thus, we can follow an established research methodology that has been used in related empirical historical studies (for instance, see Becker and Woessmann (2009) and Dittmar (2011)). However, in our case distance might be endogenous to the growth rate of a city before the implementation of the clock. The results in Table A4 in the appendix consider the distance from the very first innovators. As we illustrated in Figure 2, the cities adopting the mechanical clocks between the years 1283 and 1350, and shows a similar pattern as found in the Section 3.

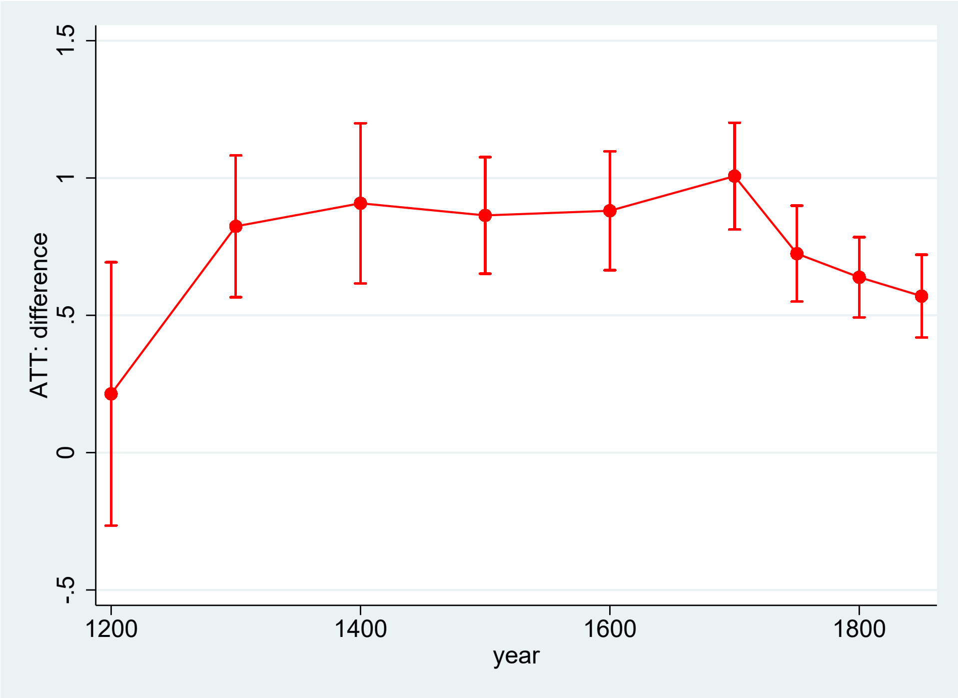
Alternatively, the increasing effect of the period between 1500 and 1700 is also confirmed by a propensity score matching technique (Rosenbaum and Rubin (1983)). More specifically, we match treatment and controls based on a logit specification reported in column (5) of Table 4. Figure 8 reports the yearly average difference of the treatment effects on the treated with respect to the control and the relative standard errors.

An additional and legitimate concern can be that the the fact that by chance total and solar eclipses might have overlapped with very active economic area (e.g., the Southern part of England, the Netherlands, and the Northern part of Italy) by chance, thus creating potential problems related to the geographical balance of the dataset. Even if regressions excluding parts of the dataset seem to exclude this,[45] we address this potential bias by adopting the estimation technique of the Entropy balancing algorithm proposed by Hainmueller and Xu (2013) and recently used by Angelucci et al. (2017). In practice, the algorithm creates in an artificial way a geographical and random balance of the cities that are not similar to the ones in the treatment group. The results are reported in Table 7, which is divided into two parts: in the upper part, we observe the comparison between treated and control before and after the weighting, respectively, while the lower part reports the results of the weighted regression. Additionally, we find consistent results as in the previous regressions.

(e.g., Card (1993)) by other studies on innovation of product and culture and economic growth (Becker and Woessmann (2009) and Dittmar (2011)).

[45] Table A4 in the Appendix shows the OLS estimates excluding Germany, Italy, the Netherlands, Switzerland, and the Atlantic ports, respectively.

Figure 8: Difference of the ATT



Difference of the ATT derived from propensity score with 95% confidence interval. Source: Authors' calculations based on the authors' dataset of clocks.

Finally, we exploit the fact that we have precise information on the data of the construction of the mechanical clock. This would allow us to check whether the results displayed before may be affected by two potential issues: first, the econometric models previously estimated do not consider the different dynamics related to the time of adoption of the public mechanical clock, which spans over a period of three different centuries; second, particularly in the OLS regressions, a potential reverse causality between the technology and the level of population. For these reasons, we can consider an event-study regression analysis in the spirit of Autor (2003),[46] which is an extended version of equation (1) with the exception of using a set of dummy variables that take the value of one once the the lags of one or two centuries are considered (i.e., $Adoption_{t-200}$ and $Adoption_{t-100}$, respectively), the century of adoption ($Adoption_t$), and the four centuries after the innovations (i.e., $Adoption_{t+100}$, $Adoption_{t+200}$, $Adoption_{t+300}$, and $Adoption_{t+400}$, respectively). We consider cities with at least three consecutive observations. Table A6 in the Appendix shows the results of the event-study considering the different moment of the adoption of the technology as different experiments over time, while Figure 9 shows the estimated impact of the public mechanical clock over the time relative to the

[46]See Angrist and Pischke (2008) for an introduction and a comparison with respect the DiD methodology.

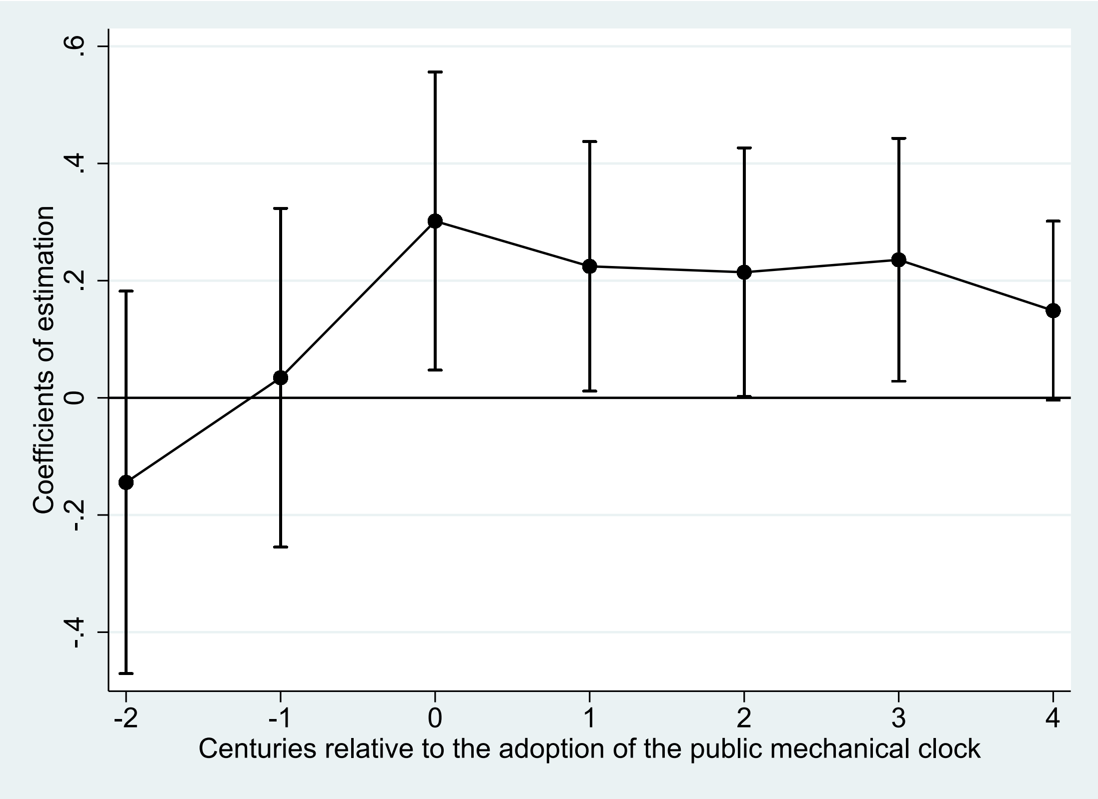
Table 7: Weighting Regressions using the entropy algorithm technique

Variable	Before the weighting		After the weighting	
	Treated	*Control*	*Treated*	*Control*
Longitude	7.65	9.39	7.65	7.65
Latitude	47.95	46.56	47.95	47.95
Calories	116,148.00	103,741.00	116,148.00	116,148.00
Atlantic	0.02	0.02	0.02	0.02
Potato	9.28	8.43	9.28	9.28
Land suitability	9.96	9.67	9.96	9.96
Ruggedness	2.45	2.56	2.45	2.45
Elevation	6.09	6.21	6.09	6.09
Weighted Regression				
$CLOCK$	1.10***			
	(0.28)			
$CLOCK \cdot Post \cdot Trend$	0.07***			
	(0.02)			
Number of observations	9,319			

On the upper part of the table comparison treated vs control before and after the weighting applying the entropy algorithm technique (Hainmueller and Xu (2013)). On the lower part OLS regression using the entropy weights. Controls considered in column (4) of Table 3 included in all regressions.

adoption. Figure 9 shows the results of column (3) of Table A6, confirming the dynamics found in the previous estimations.

Figure 9: Results from the OLS estimates with leads and lags.



Estimates from the last column of Table A6 in the Appendix. The dependent variable is the logarithm of city population before 1750. The OLS estimates include all the controls of equation (1) plus a set of leads and lags and the interactions $Country \times year$ and $Country \times year^2$.

Finally, in the Section B.1. of the Appendix we study potential effects of public mechanical clocks at the country level. For doing this, we interpolate long-run GDP per capita measures and apply the empirical framework introduced by Czernich et al. (2011). Having in mind all the caveats related to these procedures, our estimates confirmed similar patterns obtained using city-level data.

6 The long-run effect of mechanical clocks on cultural values

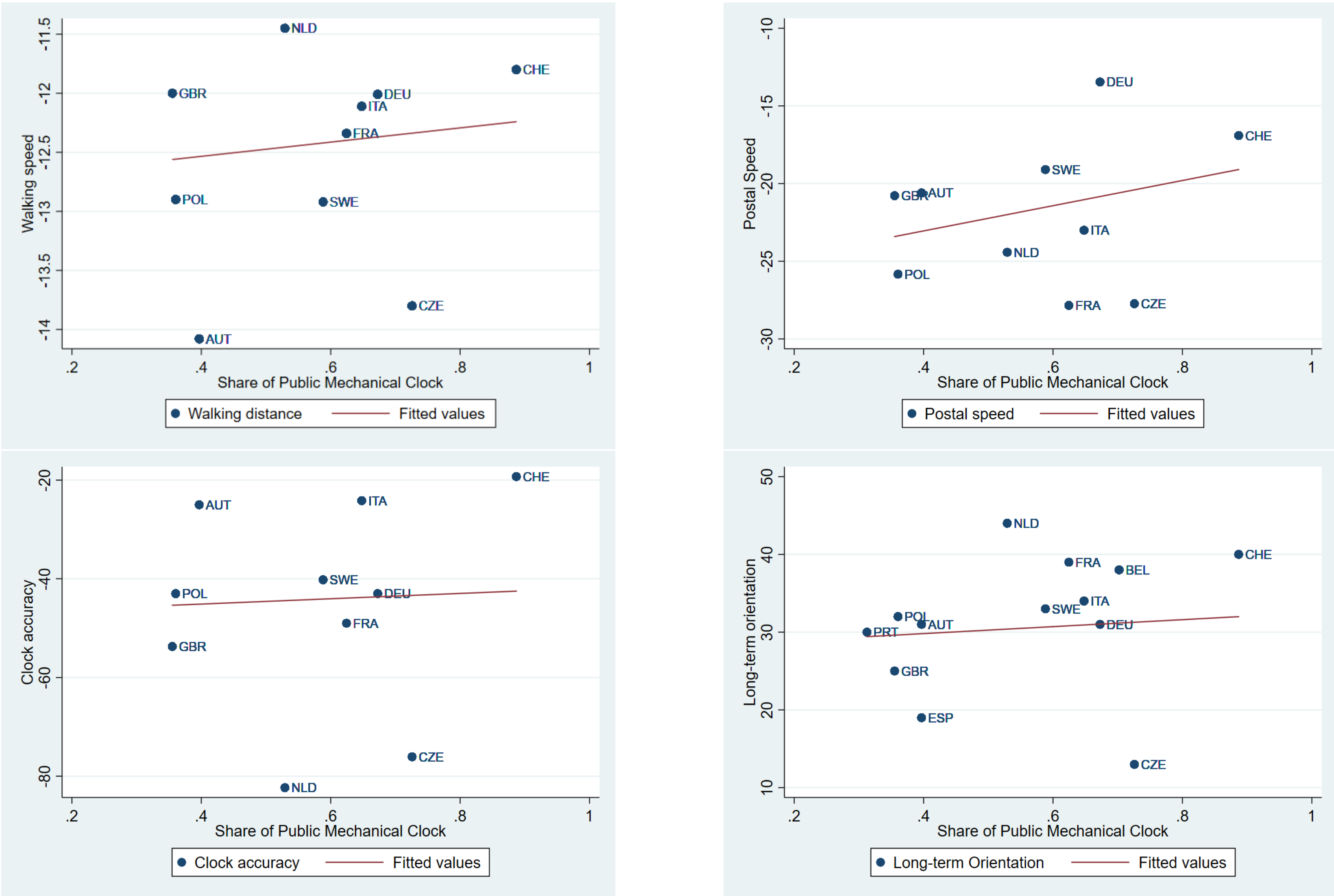
In this section, we will explore whether the early adoption of the mechanical clock had a long-term legacy in contemporary life. To the best of our knowledge, it is a very difficult task finding either micro- or macrolevel datasets containing information on firms' and individuals' time culture. However, remarkable exceptions can be found in psychological and sociological studies on the links between the peace of life and long-term orientation on societal behaviors.

Pace of life is a concept that was introduced in psychological studies (e.g., Levine (1998) and Levine and Norenzayan (1999)) and refers to the speed and rapidity of experiences, meanings, perceptions, and activities. These measures appear to be correlated with several universal features in socioeconomic activity and crime (Bettencourt et al. (2007)). For our empirical exercises, we consider three measures of pace of life collected by Levine and Norenzayan (1999). All these measures were collected in large cities in 31 countries located in Asia, Europe, and North and South America during a warm summer month between 1992 and 1995. The first measure, the walking speed, is the average (male and female) walking time needed for alone pedestrians over a distance of 60 feet measured during the main business hours during a clear summer days. The second measure, the postal speed, is the time needed by a postal clerk to sell a stamp after a standard request. The third one is the clock accuracy in the downtown bank offices during working time. Finally, a forth measure so-called Long-term orientation is instead defined by Hofstede et al. (2010) as the culture and firm organizational values that oriented toward long-term relationships and perseverance and based on data collected on IBM employees in 40 different countries.[47]

Given that these cross-sectional data can be matched with our country-level data on clocks for eleven countries, we study our relationships as mere correlations, which are represented by Figure 10. These results indeed indicate that the early introduction of a new technology can have long-run implications for the (varying) developments of societies that are related to their daily routines regarding economic and social interactions. Early implementation indeed correlates with a tighter organization and coordination of activities.

[47]Long-term orientation is one out of five measures from the so-called Hofstede Cultural Orientation Model which compares cultural values across nations. It assigns cultural preferences such as long term planning, long term benefits, values for persistence, savings, vs. short term planning, short term material or social success on an index score from 0 to 100.

Figure 10: Pace of life, long-term orientation and mechanical clocks



Source: Authors' calculations based on Levine and Norenzayan (1999), Hofstede et al. (2010), and the authors' dataset of clocks. Countries available: Austria (AUT), Belgium (BEL), Switzerland (CHE), Czech Republic (CZE), Germany (DEU), Spain (ESP), France (FRA), Great Britain (GBR), the Netherlands (NLD), Poland (POL), and Portugal (PRT).

Furthermore, according to Galor and Özak (2016), long-term orientation has a relevant impact on time preferences, which is a fundamental part of human decisions. We borrow both the estimates of the model and the dataset used by Galor and Özak (2016), which exploits the European Social Survey in 2006 and studies the cultural effects as the interdenominational transmissions of long-term orientation at the second generation immigrants.[48]

$$LTO_{ic} = \beta_0 + \beta_0^{1450} CLOCK_{ic}^P + \beta_1^{1500} yield_{ic}^p + \beta_1^{CH} \Delta yield_{ic}^p + \tag{5}$$

$$\beta_2^{1500} cycle_{ic}^p + \beta_2^{CH} \Delta cycle_{ic}^p + \beta_3 X_{ic} + \epsilon_{ic}$$

where $CLOCK^P$ is the percentage of the population of mechanical clock during 1500, LTO_{ic} is the LTO of individual i who is a second-generation migrant in country c, $yield_{ic}^p$ and $cycle_{ic}^p$ are the yield and the cycle of the crop before the Columbian Exchange, and X_{ic} is a set of additional controls.[49]

	Dependent variable: *LTO*			
	Either parent	Mother	Father	Both
	(1)	(2)	(3)	(4)
$CLOCK^P$	11.07**	13.76***	6.11	11.25
	(4.17)	(4.59)	(8.06)	(12.06)
Adjusted R^2	0.04	0.04	0.07	0.06
N. of observations	1,046	847	506	248

The empirical output of regression five, give further support for long-run orientation along the lines of Galor and Özak (2016). In particularly, the strong positive link to the mother that is documented in Figure 10 might indicate a long-term matrilineal heritage of cultural routines via the mother's side. However, as outlined before in this section, we only offer a first explorative path for further research. How in detail these behaviour patterns have evolved and preserved cannot be answered here. As outlined above, this section just should only offer a first explorative path to follow.

[48] As remarked by several studies (e.g., Fogli and Fernandez (2009) and Algan and Cahuc (2010)), the analysis of second generation immigrants helps to isolate the effect of culture from environmental conditions.

[49] More precisely, the number of year taken for transition to agriculture and gender, age, education, marital status, health status, and religiosity of the individual.

7 Conclusion

This paper studied the impact of public mechanical clocks on economic growth and development in premodern Europe. By comparing the early adopting cities of the clock (identified for the period 1293-1450) with other later or non-adopting cities, significant growth rate differences in the range of 30 percentage points can be found for the population city size, which is a good proxy variable for premodern economic growth. These differences in growth rates are identified between 1500-1700 and are therefore strongly time-lagged. These results are robust against endogeneity and thus can be interpreted as causal. To further substantiate these insights we extended the analysis to some furthermore dimensions. Among others, we introduced one of the most important subsequent technologies and drivers for economic growth, the printing press as an additional control variable, yet our results do not change. Furthermore, we investigated whether the implementation of the clock in any city of the sample had subsequent growth effects, and we find persistent growth rates over the next centuries. Finally, we showed that the penetration rate of the diffusion of the clock on a country level explains the GDP growth rate during the same identified time-lagged period.

Our findings contribute to the literature in the following way. Our quantitative results complement the qualitative insights by a broad range of social scientists who claim that clocks had an impact on work organization, culture and discipline and created higher productivity. These scholars also find strong time-lagged effects and argue that sustainable changes only started to occur only during the late 15th and mainly 16th century. Thus, whereas this literature identifies the institutional and cultural changes, our results provide the complementary spill-over effects in the form of economic output. In addition, our results shed light on the role of technology for economic development and growth before the Industrial Revolution and provide evidence on the quantitative impact of technological change triggered by the upper-tail of human capital. Furthermore, the identification of this long-run time-lagged change over several centuries sheds further light on the Solow Paradox, based upon which we started and motivated our analysis. It highlights how technological change embedded in institutional and cultural change results in long-run economic growth.

To achieve these results we collected information on the construction and use of public mechanical clocks in premodern Europe and are, to the best of our knowledge, the first ones to apply it to an empirical growth analysis. We run a wide range of standard empirical tests including (flexible) difference-in-difference, event-study, propensity-score analysis, and entropy-tests, and last but not least, we introduced solar eclipses as a new instrument for clocks to deal with misspecification, measurement errors, and endogeneity.

Finally, to extend and further explore the impact of mechanical clocks on contemporary behavior we concluded the paper with an analysis of intertemporal long-run correlation between the early implementation of clocks and contemporary cultural values and routines. These results indicate a positive relationship between an early implementation of the new technology and a tighter organization and coordination of societies, and stronger affinity to time. However these results create first of all an outlook for further investigation to understand the long-run evolution of daily routines related to fundamental technological changes in more detail.

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Time for Growth

by Lars Boerner and Battista Severgnini

Appendixes

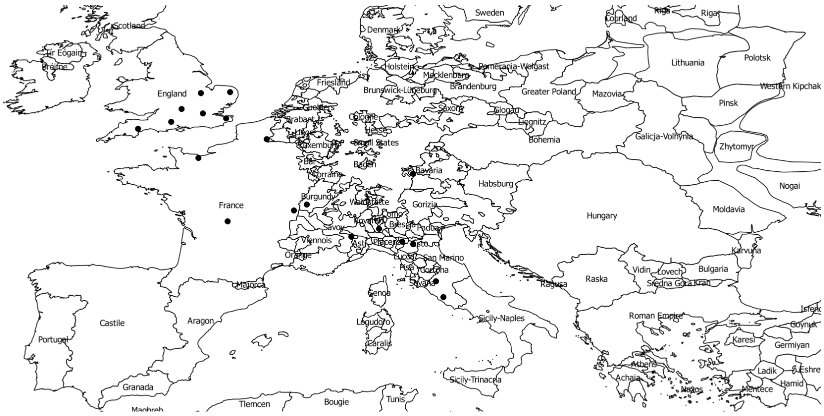
Table A1: Descriptive Statistics

Variable	**Mean**	**Standard deviation**	**Min**	**Max**
CLOCK	0.17	-	0.00	1.00
Population	13,371.74	29,248.41	1,000.00	948000.00
Longitude	9.09	11.36	-16.61	142.55
Latitude	46.79	5.93	27.90	65.01
Atlantic	0.02	0.13	0.00	1.00
Calories	105824.92	29,640.32	0.00	177882.61
Potato	12,764.99	8,671.28	1.00	31,416.94
Land suitability	20,387.72	7,917.19	1.00	31,416.94
Ruggedness	16.18	10.02	1.07	47.29
Elevation	709.56	534.85	22.69	2,924.50
Eclipse	0.29	0.46	0.00	2.00
Distance	5.82	6.81	0.00	129.66
Press	0.14	-	0.00	1.00

Descriptive statistics of the main variables used in the quantitative analysis in the paper and described in Section 3. Total number of observation 9,319.

Figure A.1 (first part): Different moment of diffusion process during 1325-1350

Diffusion until 1300



Diffusion until 1350

Figure A.1 (second part): Different moment of diffusion process durint 1370 and 1400

Diffusion until 1370

Diffusion until 1400

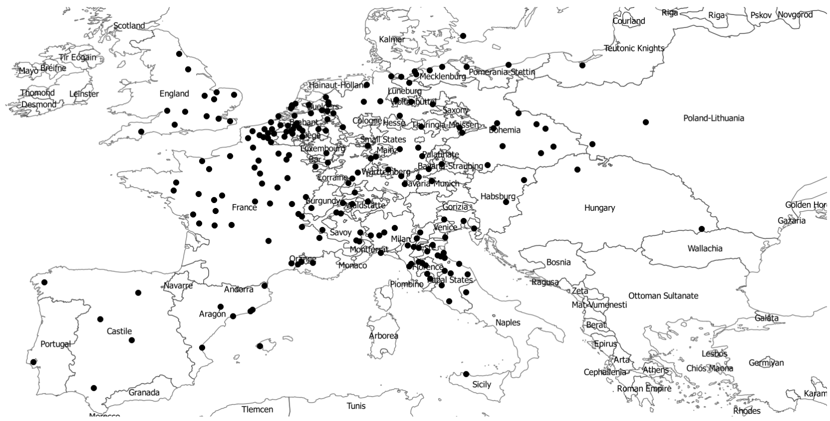


Table A2: First stage regression and partial F-test statistics

	Clock · Year								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	1200	1300	1400	1500	1600	1700	1750	1800	1850
Eclipse·									
$YEAR = 1000$	-0.19***	-0.02	-0.03***	-0.02***	-0.01	-0.02**	-0.02**	-0.02*	-0.02*
	(0.06)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$YEAR = 1300$	-0.18***	0.25***	-0.01***	-0.01	0.00	0.00	-0.01	-0.01	0.00
	(0.05)	(0.06)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$YEAR = 1400$	-0.17***	0.00	0.20***	0.01	0.01	0.00	0.01	-0.01	0.01
	(0.05)	(0.00)	(0.06)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$YEAR = 1500$	-0.18***	-0.01	-0.01***	0.20***	0.01	0.01	-0.01	0.01	0.02*
	(0.05)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
$YEAR = 1600$	-0.18***	-0.01	-0.01	0.01	0.16***	0.02*	0.00	0.02	0.02*
	(0.05)	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)	(0.01)	(0.01)
$YEAR = 1700$	-0.18***	-0.01	-0.01**	0.01	0.02*	0.16***	0.01	0.02	0.02**
	(0.05)	(0.01)	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)	(0.01)
$YEAR = 1750$	-0.18***	-0.01	-0.01*	0.01	0.02*	0.02**	0.16***	0.02*	0.02*
	(0.05)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.04)	(0.01)	(0.01)
$YEAR = 1800$	-0.18***	-0.01	-0.01**	0.01	0.02*	0.02*	0.01	0.15***	0.03***
	(0.05)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)	(0.01)
$YEAR = 1850$	-0.18***	-0.01	-0.01*	0.01	0.02	0.02**	0.01	0.03***	0.15***
	(0.05)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)
$F - test$	36.72	57.60	8.26	44.52	51.48	48.81	35.01	72.48	72.23

First stage regression coefficients of $Eclipse \cdot Year$ of the specification reported in column (5), Table 4. City and year fixed effects included in all regressions. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

Table A3: Exogeneity test

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent variable:	*Press*	*Free imperial city*	*Bishop*	*Water*	*Hanseatic*	*Log Distance to Wittenberg*	*Log Sixteenth–Century Growth*	*Log Fifteenth–Century Growth*
Eclipse	0.01	-0.01	-0.08	0.11	0.18***	-0.04	-0.08	0.03
	(0.05)	(0.04)	(0.06)	(0.08)	(0.06)	(0.08)	(0.08)	(0.11)
Adjusted R^2	0.35	0.70	0.37	0.11	0.44	0.84	0.02	-0.01
N. of observations	248	248	248	248	248	248	174	122

OLS regression based on the dataset and specification provided by Rubin (2014) and introducing the variable *Eclipse*. Significance at the 90%, 95%, and 99%, respectively.

Table A4: IV Regressions

	Dependent variable: $\ln POP$				
	(1)	(2)	(3)	(4)	(5)
$CLOCK\cdot$					
$YEAR = 1200$	0.17	0.17	0.01	-0.20	
	(0.69)	(0.70)	(0.74)	(0.79)	
$YEAR = 1300$	1.17**	1.18**	1.13**	1.01**	0.98*
	(0.48)	(0.48)	(0.45)	(0.49)	(0.51)
$YEAR = 1400$	0.82*	0.83*	0.63	0.41	0.42
	(0.48)	(0.49)	(0.41)	(0.47)	(0.56)
$YEAR = 1500$	0.78*	0.78*	0.74*	0.58	0.88*
	(0.40)	(0.41)	(0.39)	(0.46)	(0.53)
$YEAR = 1600$	0.74**	0.74**	0.71**	0.66	1.31*
	(0.34)	(0.34)	(0.32)	(0.45)	(0.68)
$YEAR = 1700$	1.09**	1.08**	1.15**	1.11*	1.32**
	(0.52)	(0.52)	(0.51)	(0.57)	(0.62)
$YEAR = 1750$	0.79	0.79	0.86*	0.58	1.24*
	(0.51)	(0.51)	(0.51)	(0.52)	(0.69)
$YEAR = 1800$	0.79	0.79	0.88*	0.54	1.28*
	(0.52)	(0.52)	(0.52)	(0.50)	(0.66)
$YEAR = 1850$	0.65	0.66	0.76	0.24	0.80
	(0.53)	(0.54)	(0.54)	(0.49)	(0.72)
Geographical coordinates	N	N	N	N	N
Atlantic harbors	N	Y	Y	Y	Y
Calories	N	N	Y	Y	Y
Geographical variables	N	N	N	Y	Y
Population at 1200	N	N	N	N	Y
p-value for joint significance $CLOCK$	0.00	0.00	0.00	0.00	0.01
Number of observations			9,319		8,572
Number of clusters			41		

Instrument considered: distance from the first adopters interacted by year. City and year fixed effects included in all regressions. Longitude and latitude not included. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively. Exogenous regressors are partialled out.

Table A5: OLS Regressions

	Dependent variable: $\ln POP$				
	(1)	(2)	(3)	(4)	(5)
Sample without:	*Germany*	*the Netherlands*	*Italy*	*Switzerland*	*Atlantic ports*
$CLOCK*$					
$YEAR = 1200$	0.29	0.13	0.17	0.13	0.12
	(0.22)	(0.25)	(0.30)	(0.24)	(0.25)
$YEAR = 1300$	0.81***	0.68***	0.75***	0.69***	0.65***
	(0.18)	(0.18)	(0.23)	(0.17)	(0.18)
$YEAR = 1400$	0.78***	0.58**	0.60*	0.58**	0.55**
	(0.17)	(0.24)	(0.30)	(0.22)	(0.23)
$YEAR = 1500$	0.56***	0.43***	0.45**	0.42***	0.41**
	(0.14)	(0.16)	(0.20)	(0.14)	(0.16)
$YEAR = 1600$	0.59***	0.46***	0.50**	0.46***	0.44**
	(0.16)	(0.16)	(0.20)	(0.15)	(0.16)
$YEAR = 1700$	0.76***	0.56***	0.64***	0.58***	0.55***
	(0.19)	(0.19)	(0.22)	(0.18)	(0.19)
$YEAR = 1750$	0.50**	0.33*	0.42*	0.34*	0.33
	(0.19)	(0.19)	(0.23)	(0.18)	(0.20)
$YEAR = 1800$	0.39*	0.22	0.28	0.23	0.20
	(0.21)	(0.22)	(0.28)	(0.22)	(0.23)
$YEAR = 1850$	0.27	0.12	0.17	0.10	0.11
	(0.24)	(0.24)	(0.30)	(0.24)	(0.26)
p-value for joint significance $CLOCK$	0.00	0.00	0.00	0.00	
Adjusted R^2	0.68	0.68	0.66	0.68	0.68
Number of observations	8,100	9,012	7,533	9,211	9,156

Controls considered in column (4) of Table 3 included in all regressions. City and year fixed effects included in all regressions. Standard errors are robust and clustered by country. All control variables are interacted by year dummies. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

Table A6: Event Study

Dependent variable: $\ln POP$	(1)	(2)	(3)
$Adoption_{t+400}$	0.16**	0.13*	0.15*
	(0.08)	(0.08)	(0.08)
$Adoption_{t+300}$	0.26**	0.20**	0.24**
	(0.10)	(0.10)	(0.11)
$Adoption_{t+200}$	0.25**	0.17*	0.21*
	(0.12)	(0.10)	(0.11)
$Adoption_{t+100}$	0.29*	0.19*	0.22**
	(0.14)	(0.10)	(0.11)
$Adoption_{t}$	0.35**	0.26**	0.30**
	(0.15)	(0.11)	(0.13)
$Adoption_{t-100}$	0.111	0.0350	0.0343
	(0.19)	(0.16)	(0.15)
$Adoption_{t-200}$	-0.48*	-0.41	-0.54*
	(0.19)	(0.19)	(0.17)
Adjusted R^2	0.81	0.82	0.83
Interaction $Year * Country$	Y	Y	Y
Interaction $Year^2 * Country$	N	Y	Y
Other variables	N	N	Y
Number of observations		7,477	

Other variables: controls considered in column (4) of Table 3 included in all regressions. Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

B. Mechanical clocks and GDP per capita

This section allows us to test whether the adoption of public mechanical clocks had a direct impact not only on the growth of towns but also on productivity in wider geographical areas. Such an aggregate study can be motivated by our consideration of GDP per capita as a measure of the aggregate performances, which allows us to make better comparisons with the related research on the recent economic impact of the information technology discussed in the introduction.[50] To test this, we take inspiration from the empirical framework introduced by Czernich et al. (2011), who analyze the effect of broadband Internet access on economic growth in European countries. The estimation is based on two stages: in the first stage, we study and predict the rate of penetration of the mechanical clock at the country level; in the second stage, we estimate the factors that are important for economic growth and detect the importance of the new technology using the findings of the first stage. For our analysis, we consider a slightly modified version of the traditional growth regression model introduced by Mankiw et al. (1992), which is considered in the second stage, and study the different effects of physical factors and technology:

$$\Delta \ln y_{ct} = \ln A_c + \gamma_2 \Delta \ln POP_{ct} + \gamma_3 \ln y_{c0} + \xi_{ct} \tag{6}$$

where for country c at time t $\Delta \ln y$ is the gross domestic product (GDP, henceforth) per capita growth rate, $\Delta \ln POP$ is the population growth, $\ln y_{c0}$ is the initial level of GDP per capita and ξ is the error term. To study the effect of clocks, we decompose the country-level of technology A_c into a general technological effect, represented by the parameter γ_0 and the contribution of the clock B_{ct}, for which the penetration rate serves as proxy:

$$A_{ct} = exp(\gamma_0 + \gamma_1 B_{ct}) \tag{7}$$

Substituting (7) into (6), we obtain the modified growth equation

$$\Delta \ln y_{ct} = \gamma_0 + \gamma_1 B_{ct} + \gamma_2 \Delta \ln POP_{ct} + \gamma_3 \ln POP_{c0} + \xi_{ct} \tag{8}$$

[50] Dale Jorgenson and associates studied in depth the relationship between IT and productivity: for example, using growth accounting techniques Jorgenson (2005) and Jorgenson and Vu (2005) analyze ITs contribution to total factor productivity for the American and the world economies, respectively.

Similar to the discussion in the previous section, here, an OLS estimate of (8) may be affected by two different endogeneity issues: first, a problem of reverse causality can arise because country economic growth can positively drive the adoption of the mechanical clock; second, there could be a problem of misspecification because particular government policies and different institutional quality, which is difficult to measure, could play a role in the adoption of the mechanical clock. For these reasons, we imitate the strategy that was introduced by Czernich et al. (2011) by considering an instrumental variable approach, which is also useful for studying the pattern of diffusion, and by considering an instrumental variable approach, which is also useful for studying the pattern of diffusion. Following the previous contributions to the adoption rate (Griliches (1957), Geroski (2000), and Comin et al. (2010)) that are also motivated by the S-shaped diffusion of technology, we model the impact of the clock B following a logistic distribution

$$B_{ct} = \frac{\phi_c}{1 + exp\left[-\tilde{\beta}\left(t - \tau\right)\right]} + e_{ct} \tag{9}$$

where ϕ_c is the saturation level, i.e., the maximum amount of adoption, $\tilde{\beta}$ is a parameter displaying the double amount of maximum growth rate, τ provides information on the inflection point of the curve and e is the error term. To provide a value for ϕ, we assume that the saturation can be positively related to the percentage of the population living in an area covered by the combinations of eclipses studied in the previous section, $eclipse\ share_c$

$$\phi_c = \phi_0 + \lambda_1 eclipse\ share_c \tag{10}$$

The availability of yearly population data described in Section 3 allow us to study the diffusion using more than 7,000 observations. More precisely, we consider population data for eight countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Sweden, Switzerland, and the United Kingdom) for the period of 1250-1750. Table B1 shows the results of the regression of the equation obtained by substituting (10) into (9), which provide several pieces of information. We can observe that the parameter of eclipses (λ_1) enters in a positive and significant way, with a a penetration rate of approximately 20%. In addition, while the parameter τ suggests that the inflection rate is situated at the year 1430, a period which is similar to those analyzed in the empirical analysis in Section 2, $\tilde{\beta}$

indicates a maximum growth rate of approximately 1.5% In addition, Figure B.1 compares the actual rate and the the fitted adoption rate generated by the first stage estimates and suggests a prevalence of logistic distributions in the countries analyzed.

Table B1: NLS estimation for the diffusion curve

	λ_1	ϕ_1	$\tilde{\beta}$	τ
	0.21***	0.00***	0.02***	1430.68***
	(0.00)	(0.00)	(0.00)	(5.30)
R^2		0.30		
N. of observations		8,421		

Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

Figure B.1.: Mechanical adoption rate: Actual (blue line) and predicted (red line)

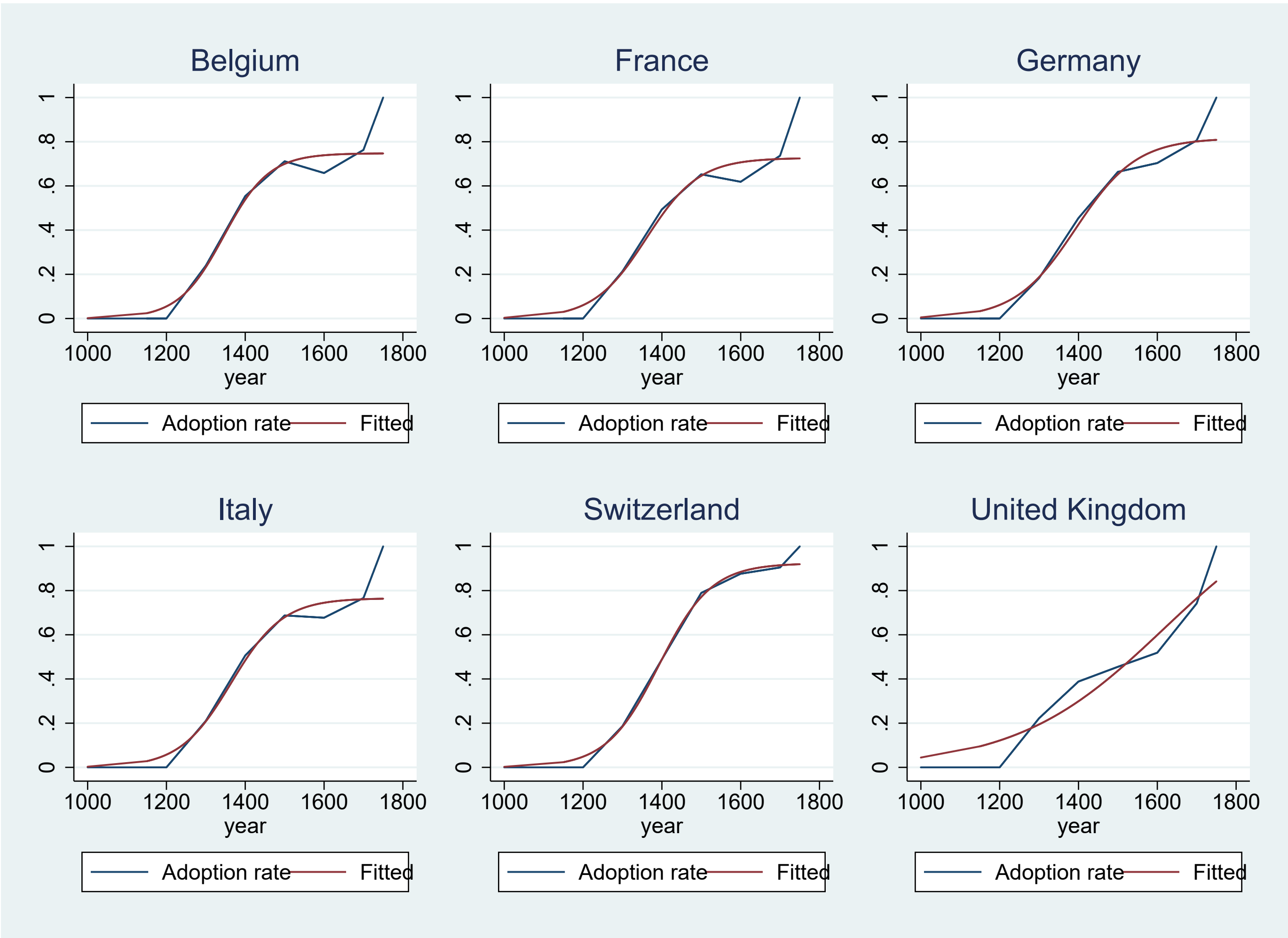


Table B1 contains the results of the second stage. The first four columns show the impact of the contemporaneous adoption of the mechanical clock ($\widehat{B}_{ct}$) on economic growth, while columns (5)-(8)

consider a lag of a century ($\widehat{B}_{ct-100}$). In all the cases, we consider both cluster and bootstrapped standard errors errors based on 50 replications. Our estimates are based on the GDP per capita each 100 years collected by Maddison (2007), and confirm the findings of the regressions based on city-level data, i.e., the penetration of the GPT has a positive and significant impact on GDP per capita growth. We find that an increase of 10 percentage points in the diffusion of mechanical clocks can raise the GDP per capita growth approximately 30 % in a century.

Table B1: The effects of mechanical clocks on GDP per capita: second stage.

	(1)	(2)	(3)	(4)		(5)	(6)	(7)	(8)
			Bootstrapped Std. Errors	Bootstrapped Std. Errors				Bootstrapped Std. Errors	Bootstrapped Std. Errors
$\widehat{B}_{ct}$	0.32***	0.32***	0.32***	0.32***	$\widehat{B}_{ct-100}$	0.33***	0.33***	0.33***	0.33***
	(0.78)	(1.13)	(0.81)	(1.69)		(0.84)	(1.23)	(0.86)	(1.82)
$\ln y_0$	0.00	0.00	0.00	0.00	$\ln y_0$	0.00	0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)	(0.00)	(0.00)	(0.00)
$\Delta \ln POP$	0.32	0.32	0.32	0.32	$\Delta \ln POP$	0.32	0.32	0.32	0.32
	(0.24)	(0.24)	(0.25)	(0.25)		(0.24)	(0.24)	(0.25)	(0.25)
$Constant$	1.23*	1.23*	1.23**	1.23**	1.23*	1.23*	1.23**	1.23**	
	(0.56)	(0.56)	(0.51)	(0.51)	(0.56)	(0.56)	(0.51)	(0.51)	
R^2	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	
N. of observations					36				

Significance at the 90%, 95%, and 99% confidence levels are indicated by *, **, and ***, respectively.

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