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<https://doi.org/10.1057/s41599-025-05283-z>

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Cultural innovations were boosted under the pressure of epidemic outbreaks in European History

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Outbreaks of epidemics are human ecological disasters and have caused huge losses of human life and social disturbances in human history. But their impact on human culture has never been systematically and quantitatively studied. This study hypothesizes that such gigantic human ecological pressure would have created a great need for cultural innovations. By quantitatively examining and modeling the process using the time-series of cultural innovations and human ecological-socioeconomic proxies in European history (1000–1900 CE) based on the basic principles of causal inference, the paper demonstrates that infectious disease epidemics and socioeconomic stress stimulated the flourishing of thinkers and philosophical thoughts across different philosophies in truth, knowledge, and ethics, and promoted scientific discovery/technological innovations in a macro scale. Based on the results of Poisson regression and analysis of marginal effects, when the epidemics increased by 1, the average number of philosophical thinkers increased by 0.85, and their average impact score increased by 4.04. When the Consumer Price Index (CPI) increased by 0.1, the average number of philosophical thinkers increased by 8.9, and the average impact score increased by 29.79. The results of linear regression further show that when the epidemics increased by 1, the average scientific discoveries and technological innovations (SDTI) increased by 0.128 units; when CPI increased by 10%, the average SDTI increased by 0.15 units. Infectious disease epidemics have generally played an important role in generating cultural dynamics during the study period. The results imply that the recurrent outbreaks of the COVID-19 pandemic would likely lead to another thriving phase of cultural innovations.

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Introduction

The current pandemic of COVID-19 and its variants poses a great human ecological crisis with several millions of deaths and has led to a severe global economic recession, making it one of the deadliest pandemics in history and creating a huge impact on almost every aspect of human life and society (Zumbrun, 2020). It has not only created new problems but also magnified existing social problems in many societies and nations. From social distancing measures to political conflicts between countries, such an impact has shaken the cultural grounds of some existing political systems, social organizations, and interpersonal relationships and created new demands on cultural innovation, science, and technology globally (Azoulay and Jones, 2020). But questions remain: could these demands deriving from this ecological disaster be converted into reality in human societies? If they could, can we provide empirical evidence and theoretical support to verify it?

In human history, outbreaks of epidemics killed hundreds of millions of people and were the most demographically or socio-economically significant among human ecological disasters. However, humans have highly developed brains and are capable of abstract reasoning, language, introspection, and problem-solving (MacIntyre, 1999; Flanagan, 2009). One result of the ecological disasters and the consequent socioeconomic crises is that human beings have employed the intellectual capability to adapt to ever-changing ecological conditions, initiating the cultural evolutionary process through which human beings find their way around the new environment (Zhang et al., 2020). Therefore, historical infectious disease epidemics, as the deadliest human ecological disasters, have created socioeconomic crises and led to an upsurge of innovative cultural ideas and actions in ways that transform and strengthen the resilience of human communities and individuals.

A conceptual model showing how infectious disease epidemics stimulated cultural innovation is proposed to demonstrate the hypothesized links (see Fig. 1). This research will quantitatively verify all conceptual links between epidemic disasters and their consequent socioeconomic downturns, and cultural dynamics during a period with a sufficient number of historical records (Supplementary Section 1). We strictly follow the basic process of causal inference (Supplementary Section 2), which has been applied to science, medicine, economics, and epidemiology, to determine whether infectious disease epidemics and socioeconomic crises (independent variables) had actual effects on cultural innovations (dependent variables) in a larger human system. To clarify, we accept that other factors may affect cultural innovations as mentioned by existing theories, in addition to our adopted indicators. The aims of this analysis on the epidemics and cultural response relationship do not refute other hypotheses, which have explained cultural innovations from various causes of social, political, and economic phenomena. However, the focus of this study is different from its predecessors in terms of both temporal/spatial scales and hierarchies of reasoning (levels of quantitative association). The quantitative and philosophic approach adopted in the study would help to discover temporal patterns of infectious disease epidemics associated with the emergence of continental cultural dynamics from a macro scale.

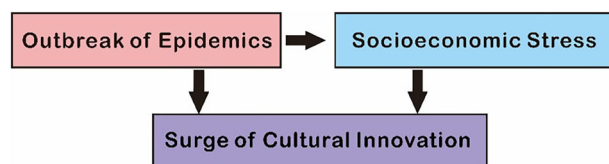


Fig. 1 Conceptual model of hypotheses proposed in this study.

Rich historical records on the European continent have supported a quantitative and causal approach in this study. Given that we need to address whether infectious disease epidemics stimulated dynamic cultural innovation from a long-term historical perspective, macro-historical and aggregate features are favored more than micro-historical and individual ones. General trends are preferred instead of moments or events. Broad distinctions or geographical uniformities (Europe) take precedence over localized analyses in this study. Cultural innovation covers all innovations of cultural expressions in both non-material and material aspects (Macionis and Gerber, 2011). The best and countable indicators of immaterial cultural innovation selected in this study are innovative thinkers and their impact score, which transfer concepts, ideas, and notions through speech and writing, to represent non-material culture (Macionis and Gerber, 2011). The innovative non-material cultures can be materialized by scientific discoveries and technological innovations (SDTI) that can be regarded as another important indicator to represent innovative culture, although part of scientific discovery is considered as non-material, such as scientific methods (Daniel, 2012). Using a big dataset of innovative thinkers (Thinker) and their impact measured by quotation scores (Score) (Sorokin, 1937), the scientific discoveries and technological innovations (SDTI) (De Dreu and van Dijk, 2018), as well as the records of infectious disease epidemics (Epidemics), CPI, and Population during 1000–1900 CE, this study has quantitatively examined the hypothesized links in European history based on the basic principles of causal inference.

Materials and methods

Variables and data. Using historical data in Europe from 1000–1900 CE, we applied several statistical methods to examine the hypothesized links between infectious disease epidemics, socioeconomic crises, and cultural innovations based on the basic principles of causal inference. Cultural innovations were set as the dependent variables.

As hypothesized links, human ecological socioeconomic crises, including infectious disease epidemics (Epidemics) and CPI, were set as the independent variables. Our epidemic data were mainly retrieved from *The Encyclopedia of Plague and Pestilence*, which is a compendium of geo-historical information about major, outstanding, and unusual epidemics in regions of the world from ancient times to the present (Kohn, 2001). It was also supplemented by Cliff et al.'s (1998) list of major infectious disease epidemics in world history printed in *Deciphering Global Epidemics: Analytical Approaches to the Disease Records of World Cities, 1888–1912* as well as Xiao and Liu's (2005) epidemic chronology printed in *History of Pestilence*. Then 1072 epidemics in Europe during 1000–1900 CE were counted based on the duration of epidemics. Infectious disease epidemics, like other large-scale human crises, could seriously influence socioeconomic conditions. CPI is thus selected in this study because it is one of the most important indicators to reflect social well-being and socioeconomic conditions (Hubbard and O'Brien, 2009). Natural and manmade calamities in the past were often associated with high CPI value (hyperinflation) and such a typical case of hyperinflation has also been witnessed during the period of COVID-19 from 2020 to 2022 (Cavallo, 2024). The high CPI level will dampen the social stability and development, which is usually included to review past social dynamics (Horrell, 2023; Ljungberg, 2025). Our CPI data have been calculated based on a basket of goods for daily needs from 18 major cities in pre-industrial Europe. More details on data source and processing are provided in Supplementary Section 1.

Table 1 Pearson's correlation.

	CPI	Score	Thinker	SDTI
Epidemics	0.514** ($P < 0.01$)	0.721** ($P < 0.01$)	0.705** ($P < 0.01$)	0.491** ($P < 0.01$)
CPI		0.952** ($P < 0.01$)	0.950** ($P < 0.01$)	0.748** ($P < 0.01$)
Score			0.995** ($P < 0.01$)	0.878** ($P < 0.01$)
Thinker				0.865** ($P < 0.01$)

P represents *P*-value, which is shown in parentheses; **significant at the 0.01 level (two-tailed).

Table 2 Multivariate poisson regression on Score and Thinker.

Dependent variables	Independent variables				Pseudo- R^2
	Intercept	Epidemics	CPI	Population	
Score	5.583** ($P < 0.01$)	0.023** ($P < 0.01$)			0.555
	5.327** ($P < 0.01$)		1.089** ($P < 0.01$)		0.768
	5.170** ($P < 0.01$)	0.008** ($P < 0.01$)	0.935** ($P < 0.01$)		0.819
	5.241** ($P < 0.01$)	0.005** ($P < 0.01$)	0.378** ($P < 0.01$)	0.005** ($P < 0.01$)	0.845
Thinker	4.403** ($P < 0.01$)	0.021** ($P < 0.01$)			0.514
	4.106** ($P < 0.01$)		1.033** ($P < 0.01$)		0.746
	3.991** ($P < 0.01$)	0.006** ($P < 0.01$)	0.904** ($P < 0.01$)		0.782
	4.051** ($P < 0.01$)	0.004** ($P < 0.01$)	0.417** ($P < 0.01$)	0.004** ($P < 0.01$)	0.803

P represents *P*-value, which is shown in parentheses; **significant at the 0.01 level.

Cultural innovation covers innovations of material and non-material cultural expressions (Macionis and Gerber, 2011). A big dataset of 13,497 innovative thinkers with a total of 36 philosophical categories of western culture was collected by Sorokin (1937), of which original datasets from the book are attached in the Supplementary Section 1. The thinkers were defined as the founder of a school of philosophical thought and the creator of an original complete system of philosophy and epistemology in the norms, ethics, beliefs, values, knowledge, existence, and language of Western culture, and their impacts were measured by the quotation scores of each philosophical thinker by Sorokin (1937) (Supplementary Section 1.3). The number of thinkers (Thinker) and their quotation scores (Score) during 1000–1900 CE were selected as the indicators of non-material cultural innovation, which transfer concepts, ideas, and notions through speech and writing (Macionis and Gerber, 2011). The scanned original pages from Sorokin's work (1937) have been attached in the Supplementary Materials. Innovative non-material cultures can be materialized by scientific discoveries and technological innovations (SDTI), which is regarded as an important indicator to represent innovative culture, although part of scientific discovery is considered non-material, such as scientific methods (Daniel, 2012). The longest and yearly SDTI record was worked out by De Dreu and van Dijk (2018).

Statistical analysis. Statistical analyses are used to certify the strength, consistency, temporality, and predictability between the variables for establishing the linkages. Following five criteria of causal inference as discussed in Supplementary Section 2, different statistical approaches will serve different purposes in each step of causal inference (Supplementary Table S1). First, Pearson's correlation analysis (Table 1) was applied to reveal the strength of association between each variable (Criterion II, Supplementary Table S1). The Pearson's correlation coefficient is the most common way of measuring a linear correlation. It has a value between -1 and 1 , with a value of -1 meaning a total negative linear correlation, 0 being no correlation, and $+1$ meaning a total positive correlation (Williams et al., 2020). Second, multivariate Poisson and linear regression approaches were applied for modeling the

consistency and predictability between the hypothesized dependent and independent variables (Criterion III and V, Table S1). Given that the data of dependent variables, i.e., Score and Thinker, are in the format of count number, the analysis of these variables has been conducted by Poisson regression (Table 2), which is regarded as the benchmark model for count data (Cameron and Trivedi, 1998). Multivariate linear regression (Table 3) was further applied to the data series of SDTI, Score, and Thinker. According to Zhang et al. (2020), Score and Thinker have a close relationship with European population (Zhang et al., 2020), yet De Dreu and van Dijk (2018) found that SDTI has no linkage with population (De Dreu and van Dijk, 2018). Therefore, the population factor has been considered in the regression on Score and Thinker, but not in SDTI. Because SDTI is a continuous variable but not count data, Poisson regression is thus only applied to Score and Thinker rather than SDTI. In addition, due to the obvious trend in data structure, the log-transformations (LN, natural logarithm) of Score, Thinker, CPI, and Population have been conducted to stabilize the variances of these variables (Durbin et al., 2002) and make them suitable for use in the linear regression (Tsiatis, 1990; Smith, 1993). Third, Granger causality analysis (GCA) and the Poisson-GCA model were adopted to verify the causal routes and predictability in our conceptual model, which could establish the hypothesized the cause/effect routes in term of temporality (Criterion IV and V, Table S1 in Supplementary Materials).

Results

Association of epidemic events and cultural innovation. We first identified whether the historical cultural booming phases cohered with the stress periods (both infectious disease epidemics and CPI rise) based on the observation of data series (see Fig. 2). Due to the fast increase in cultural innovations and ecological/socioeconomic variables in the late stage of the study period, the raw datasets of these variables were detrended by the singular spectrum analysis in R software (version 4.0.5) and smoothed by a 100-year Butterworth low-pass filter in MATLAB (version R2020b), which was only adopted for figure-making rather than statistical analysis. The detrended time-series of Thinker, Score, and SDTI are marked by robust secular movements on the

Table 3 Multivariate linear regression on Score, Thinker, and SDTI.					
Dependent variables	Independent variables				Adjusted-R ²
	Constant	Epidemics	CPI(LN)	Population(LN)	
Score(LN)	5.062** (<i>P</i> < 0.01)	0.030** (<i>P</i> < 0.01)			0.515
	6.390** (<i>P</i> < 0.01)		2.047** (<i>P</i> < 0.01)		0.803
	6.293** (<i>P</i> < 0.01)	0.003 (<i>P</i> = 0.529)	1.936** (<i>P</i> < 0.01)		0.799
	−16.097† (<i>P</i> < 0.01)	−0.005 (<i>P</i> = 0.318)	1.094** (<i>P</i> < 0.01)	1.219* (<i>P</i> < 0.05)	0.836
Thinker(LN)	3.999** (<i>P</i> < 0.01)	0.026** (<i>P</i> < 0.01)			0.484
	5.140** (<i>P</i> < 0.01)		1.857** (<i>P</i> < 0.01)		0.810
	5.094** (<i>P</i> < 0.01)	0.001 (<i>P</i> = 0.738)	1.804** (<i>P</i> < 0.01)		0.804
	−14.884† (<i>P</i> < 0.1)	−0.005 (<i>P</i> = 0.210)	1.053** (<i>P</i> < 0.01)	1.088* (<i>P</i> < 0.05)	0.840
SDTI	−0.666** (<i>P</i> < 0.01)	0.278** (<i>P</i> < 0.01)			0.240
	−0.213** (<i>P</i> < 0.01)		1.674** (<i>P</i> < 0.01)		0.539
	−0.488** (<i>P</i> < 0.01)	0.128** (<i>P</i> < 0.01)	1.461** (<i>P</i> < 0.01)		0.580

P represents *P*-value, which is shown in parentheses; †significant at the 0.1 level; *significant at the 0.05 level; **significant at the 0.01 level. Variable (LN) means the natural logarithm of this variable.

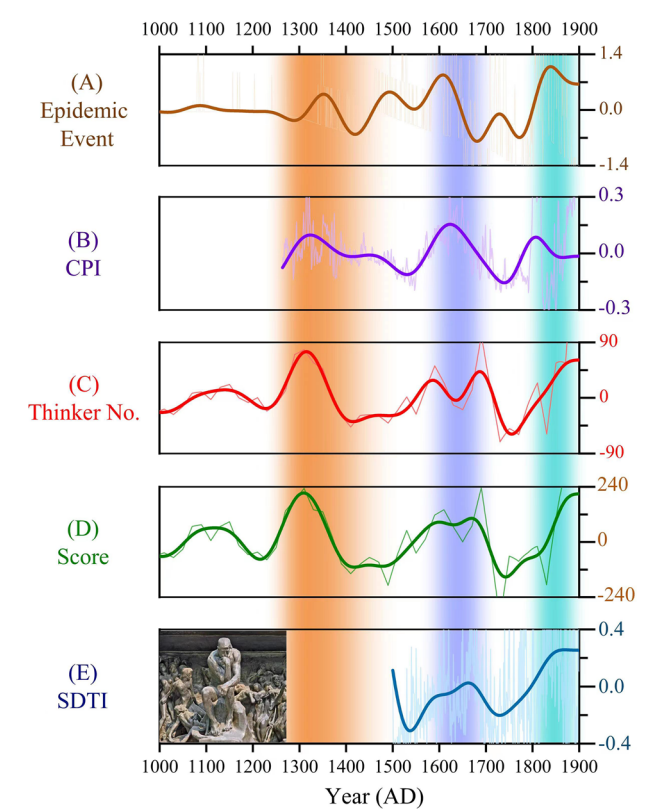


Fig. 2 Variations of European historical epidemics, socioeconomic stresses and cultural innovations during 1000–1900 CE. **A** Epidemic event (brown, number of incidents); **B** CPI (purple); **C** Thinkers (red, number of persons); **D** Score of thinkers (green); and **E** Scientific discovery and technological innovations (blue). All datasets are detrended by the singular spectrum analysis and smoothed by a 100-year Butterworth low-pass filter. The thin and thick lines represent the detrended and smoothed data, respectively. The picture on the left of Fig. 2E is the *Thinker in The Gates of Hell* at the Musée Rodin (<https://commons.wikimedia.org/w/index.php?curid=24671002>). This figure is covered by the Creative Commons Attribution 2.0 Generic License. Reproduced with permission of Jean-Pierre Dalbéra; copyright © Jean-Pierre Dalbéra, all rights reserved. The shades denote the three great cultural innovation periods in European history: the Renaissance (the gradient ramp from orange to white), the Enlightenment (light blue), and the Age of Revolution (cyan).

multidecadal to centennial scale as demonstrated by previous studies (Sorokin, 1937; Zhang et al., 2020; Jones and Weinberg, 2011), with strong sensitivity to the rhythms of epidemic event variations in Europe during 1000–1900 CE, 1264–1900 CE, and 1500–1900 CE.

The historical fluctuations of the epidemic events and cultural dynamics show that all the hypothesized independent and dependent variables in the time-series have similar rhythms and synchronic variations precisely on a macro-historical scale (see Fig. 2). Although SDTI has a shorter time collection (1500–1900 CE), its fluctuations also follow both epidemics and non-material culture variables (see Fig. 2). The peaks of epidemic fluctuation contain three well-known cultural innovation periods in European history: the Renaissance (started in Italy in the 14th century), Enlightenment (17–18th centuries), and Age of Revolution (1789–1848 CE). There is a short-term fall (about 30 years) of the innovations in the early 17th century as shown in Fig. 2, which might have been caused by the negative impact of wars on innovation (Simonton, 1976), most possibly the Thirty-Years War. However, booming of the cultural innovations during the Enlightenment period is still obvious before or after the early 17th century.

From the observation, we could empirically see similar fluctuating patterns among these data series. The results of Pearson’s correlation test have also revealed that all cultural innovation variables, i.e., Thinker, Score, and SDTI are positively and highly inter-correlated at the 0.01 level (Table 1), demonstrating that human philosophical intelligence and science/technology developed simultaneously. The two independent variables of Epidemics and CPI are also positively intercorrelated at the 0.01 level, showing a strong association between the two. The examination of Pearson’s correlation coefficients for all variables indicates that all hypothesized independent and dependent variables are quantitatively linked to each other in the study period. Based on the observation and Pearson’s correlation test, the results have demonstrated the strength and synchronicity between the hypothesized independent and dependent variables.

Linkages from epidemics and socioeconomic stress to cultural innovation. Table 2 shows the results of Poisson regression on Score and Thinker. In the first row of each panel, the coefficients of Epidemics are significantly positive at the level of 0.01, indicating that more occurrence of Epidemics is likely to be accompanied by an increase in Score and Thinker. The coefficients of

CPI are significantly positive ($p < 0.01$) in the second row of each panel, revealing that higher CPI statistically correlates with higher Score and more Thinker. If we add Epidemics and CPI together into the model, as shown in the third row, their coefficients are still significantly positive ($p < 0.01$) in the regressions. If we add Population, the results of Epidemics and CPI are consistent, and the effect of Population is also significantly positive. Calculating the average marginal effects of the results in the fourth row shows that when the number of Epidemics increases by 1, the average Score will increase by 4.04, and the average number of Thinker will increase by 0.85. When CPI increases by 0.1, the average Score will increase by 29.79, and the average number of Thinker will increase by 8.9. The marginal effect from epidemics and CPI will increase under more epidemics and higher CPI, thereby more significantly affecting cultural dynamics (see Supplementary Fig. S1).

Multivariate linear regression has been performed and the results are shown in Table 3. Similarly, the coefficients of Epidemics and CPI are significantly positive in the first and second rows of each panel, i.e., more Epidemics or higher CPI still statistically correlated with higher Score, more Thinker, and SDTI. If we add Epidemics and CPI together into the model, as shown in the third row, the coefficients of CPI are still significantly positive in three models, whereas Epidemics are insignificant in the regressions of Score and Thinker. Thus, CPI seems to have a more important impact on Score and Thinker than Epidemics. The results show that when the number of Epidemics increases by 1, the average SDTI will increase by 0.128 units. When CPI increases by 10%, the average SDTI will increase by 0.15 units. If we add population into the model of Score and Thinker, as shown in the fourth row, the coefficients of Epidemics are insignificant, while those of CPI still keep robust. When CPI increases by 1%, the average Score will increase by 1.09%, and the average number of Thinker will increase by 1.05%. Population also shows a significant effect on Score and Thinker. By summarizing all regression tests, the effect of Epidemics and CPI on the dependent variables are consistent and predicable and their relationships are fully established.

Compared with Epidemics, CPI seems to have a larger contribution to cultural innovation. However, two independent variables are correlated with each other and possibly interact with one another (Zhang et al., 2011; Pei et al., 2015). To resolve this, causal analysis was adopted because it can examine which variable proceeds or predicts another in terms of temporality by cross-examination between the two (Table 4 and Supplementary Materials). The causal analysis conducted in the study follows the

five criteria of causal inference and the relevant methods to satisfy each criterion in Supplementary Section 2.

In Table 4, the linkage “Epidemics $\rightarrow$ CPI” is statistically significant ($p < 0.1$), while the reversed linkage “CPI $\rightarrow$ Epidemics” is insignificant, meaning that in most cases, the increase/decrease of historical epidemic events proceed or lead to the increase/decrease of CPI over time, but the reverse causation does not exist. CPI is the best socioeconomic indicator that reflects the total impacts of social and natural conditions (Hubbard and O’Brien, 2009), including epidemics (Pei et al., 2022). Therefore, this explains why CPI’s effect on cultural innovation is stronger than that of Epidemics in empirical examinations (Tables 1 and 3). In addition, GCA was applied to statistically verify the causal relationship between the annual continuous variables, i.e., Epidemics/CPI and Epidemics/SDTI. Then, the Poisson-GCA model was further implemented to test the statistical strength among the links between ecological socioeconomic crises (Epidemics and CPI) and the counting variables (Score and Thinker) (Supplementary Section 3). The results in Table 4 show that the linkages of “Epidemics $\rightarrow$ SDTI,” “Epidemics $\rightarrow$ Thinker,” “Epidemics $\rightarrow$ Score,” “CPI $\rightarrow$ Score,” and “CPI $\rightarrow$ Thinker” are significant ($p < 0.05$), but the linkage of “CPI $\rightarrow$ SDTI” is insignificant. Therefore, Epidemics, SDTI, Thinker, and Score have significant results in causal analysis. However, CPI and Score/Thinker have significant results in causal analysis but not SDTI. Based on these results, the causal routes in our conceptual model (see Fig. 1) have been empirically established. We further have tested a possible conversed causal route—“culture innovation $\rightarrow$ epidemic”, based on the co-evolution theory. The insignificant results (p value is over 0.05 or even 0.1) of “Thinker $\rightarrow$ Epidemic”, “Score $\rightarrow$ Epidemic”, and “SDTI $\rightarrow$ Epidemic” suggest that above three linkages cannot pass the Granger Causality Analysis and get rejected by the causal inference, which implies that the cultural innovations were not a major agent that led to infectious disease epidemics during the study period.

Discussion and conclusion

Nobel Prize laureate Herbert A. Simon and philosopher Nicholas Rescher (1966) claimed that a causal relation is a function of one variable (the cause) onto another (the effect) (Simon and Rescher, 1966). These quantitative examinations in the study have verified the strong and consistent temporality and predictability of the hypothesized independent and dependent variables. These empirical studies satisfied four of the five criteria of causal conditions of scientific research (Haring et al., 1992; Zhang et al., 2011), which is a generalization of the Bradford Hill criteria (Hill, 1965). The last step in the causal inference is to explain the plausibility of the three linkages, that is whether Epidemics has a function on CPI and both Epidemics and CPI have direct functions on the cultural innovation variables. The function of Epidemics on socioeconomic conditions, especially on CPI, has been studied on different temporal and spatial scales, and the common conclusion of these studies has shown that infectious disease epidemics have generated socioeconomic stress (Seiler, 2020; Shao, 2020; Jedwab et al., 2021). How CPI or socioeconomic condition, with the superposed conditions of climate change, generated dynamic cultural innovations has also been verified (De Dreu and van Dijk, 2018; Zhang et al., 2020). Based on our results, we could argue that Epidemics also has an important effect to generate cultural innovations at a macro scale in the study.

Modern human evolution and civilization began with cultural innovations. The rate of cultural innovation is neither linear nor progressive (Harrington and Gelfand, 2014; Kolodny et al., 2015).

Table 4 Causal analysis.		
Linkage	F	P
EPIDEMICS $\rightarrow$ CPI ^a	2.06	0.085 [†]
CPI $\rightarrow$ EPIDEMICS ^a	1.30	0.179
EPIDEMICS $\rightarrow$ SDTI ^a	2.02	0.013 [*]
CPI $\rightarrow$ SDTI ^a	1.02	0.425
SDTI $\rightarrow$ EPIDEMICS ^a	0.99	0.428
EPIDEMICS $\rightarrow$ SCORE ^b	25.73	<0.01 ^{**}
EPIDEMICS $\rightarrow$ THINKER ^b	7.21	<0.01 ^{**}
SCORE $\rightarrow$ EPIDEMICS ^b	0.65	0.514
THINKER $\rightarrow$ EPIDEMICS ^b	1.42	0.154
CPI $\rightarrow$ SCORE ^b	12.84	<0.01 ^{**}
CPI $\rightarrow$ THINKER ^b	4.42	<0.01 ^{**}

[†]Significant at the 0.1 level ^{*}significant at the 0.05 level; ^{**}significant at the 0.01 level.
P represents P-value. For more information on causal analysis, kindly refer to Supplementary Materials.
^aThe linkages were tested by GCA.
^bThe linkages were tested by Poisson regression modified from GCA.

The basic causes of cultural innovation, such as selective pressure, cognitive capacity development, competition, and curiosity, have been explored in different academic disciplines of existing studies (Bettencourt et al., 2007; Lindholm, 2018). However, drawing insights from cognitive science, psychology, archeology, cultural evolution, and even animal behavior, the basic driving forces for human innovation are focused on necessity and curiosity (Fogarty et al., 2015; Lindholm, 2018). Curiosity is an intrinsic motivation of human nature (Gross et al., 2020) and could be considered as a constant parameter in the study period, but necessity is a variable that changes with time. The variation of necessity mainly comes from the ever-changing ecological and social conditions, creating the great need for cultural adaptations in human history. The proverb “necessity is the mother of invention” holds at different temporal-spatial scales.

At archeological timescales, cultural evolution and accumulation accelerated in difficult or variable environments and slowed in more stable or benign environments (Shamay-Tsoory et al., 2011; Sharon et al., 2011; Kuhn, 2012). At multidecadal/centennial and fine-grained scales, the stressful socioeconomic conditions under climate changes/shocks fostered cultural innovations (De Dreu and van Dijk, 2018; Zhang et al., 2020). Outbreaks of epidemics bring about not only social and economic stress but also great physical and psychological impacts on human beings. Such impacts include the physical problems from unexpected infectious disease epidemics and the consequential mental stress of harboring deeper feelings of pain, weakness, disbelief, shock, denial, or outrage, coupled with an inability to deal with such challenges. Human beings are thus eager to seek solutions from philosophy and science/technology. A greater number of thinkers and philosophical literature thus quite probably occurred in the periods of epidemic outbreaks and Epidemics significantly drive the cultural innovation variables in the empirical analyses (Tables 1–4). Such mental stress-generated creativity has also been verified by psychological experiments at the individual, group, and small-organization levels (Byron et al., 2010). Therefore, the plausibility of these explanations satisfies the requirements of causal inference (Criterion I, Supplementary Table S1), and the hypothesized linkages have satisfied all criteria at the macro scale of this study.

The process of stress-generated cultural innovation shares similarities with the stress-generated mutation in genetic research, which is a very important force to drive the natural selection for organism evolution (Hoffmann and Parsons, 1991; Bijlsma and Loeschcke, 2013). Recent studies also demonstrate that cultural evolution now holds the potential to bring together some disparate fields in science and social sciences within a unified explanatory and ontological framework (Boyd, 2018; Heyes, 2018). But the pace of cultural innovation proceeds much more quickly than genetic evolution (Stanford, 2020). Cultural innovations may also be planned, and they are often advantageous to the inventor and universally realized, and more frequently and purposefully realized when it is most needed and denotes recurrent and reversible phenomena that are rare in natural selection (Zhang et al., 2020).

Our time-series analyses and explanations have established a causal relationship between epidemics and cultural innovations over a long history based on the five criteria of causal inference and provided an excellent sample for the theory of stress-induced cultural innovation and evolution. Cultural innovations usually occur during the development of human civilization, and many other natural and social factors, including the superposed factor of climate change, could also create physical, mental, social, and economic stress on individuals and societies. Outbreaks of epidemics directly and indirectly generated robust secular and short-term movements of cultural innovation in this empirical study, indicating that infectious disease epidemics generated great

additional cultural innovations in European history. From our quantitative results and theoretical/literature support in this multidisciplinary research, we could argue that infectious disease epidemics is one of many causal factors that generated the upsurge of cultural innovations for the last millennium, although other alternative cause-and-effect explanations should also be explored. Again, we agree that the impact of other socioeconomic factors on cultural innovations during historical periods needs further investigation in other spatiotemporal scales.

Auguste Rodin placed his muscled heroic sculpture “*The Thinker*” at the front of a feature of a group of hopeless people with physical and spiritual torment in another famous sculpture of his called “*The Gates of Hell*” (Zelanski and Fisher, 2011). Such placement may have reflected a strong need for intellect and physical strength to pull through human suffering (see Fig. 2). Our empirical evidence and theoretical support have verified that the strong need can be converted into reality. Case studies also support this empirical explanation. In history, the vaccine invention was related with outbreak of smallpox in London during late 18th century and inventor, Edward Jenner, has been named as the “father of immunology” (Baxby, 2009). To block the spread of infectious diseases, terms of “quarantine” and “social distancing” as the social practices were first applied during the Black Death plague (Ott et al., 2007; von Csefalvay, 2023). In addition to the historical cases, the fight against HIV also promotes the cultural changes. Socio-cultural level factors in HIV prevention and intervention have been progressed, such as social support and sexual behaviors (Qiao et al., 2014). Furthermore, some techniques and procedures to prevent HIV infections have been advanced, for example, during the blood donation in USA (Chamberland et al., 2001). Last but not least, we have seen an increase in debates about existence, reason, knowledge, values, mind, and ethics among organizations, individuals, and scholars, and an upsurge of scientific discoveries and technological innovations in medicine, which are adaptive responses of culture to the threats of the COVID-19 pandemic, the greatest pandemic in the last 100 years and the worst economic crisis (Hyperinflation) since the Great Depression” (Zumbrun, 2020). There are significant advances in technology directly or indirectly linked with the COVID-19 pandemic, for example, which has served as a driver of digital acceleration of technology (Scarlat et al., 2022). In sum, our study on the relevant past would most likely usher in a new wave of cultural innovation under epidemics as well as other kinds of ecological-social-economic stresses based on our research results from historical lessons.

Data availability

All data generated or analyzed during this study are included in these published books, articles, and websites: Kohn (2001), Cliff et al. (1998), Xiao and Liu (2005), Simonton (1980), De Dreu and van Dijk (2018), Sorokin (1937), McEvedy and Jones (1978), the International Institute of Social History (<http://www.iisg.nl/hpw/data.php#europe>), and Allen–Unger Global Commodity Prices Database (<http://www.gcpdb.info/index.html>).

Received: 8 February 2023; Accepted: 10 June 2025;

Published online: 01 July 2025

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Acknowledgements

This work was generously supported by the National Natural Sciences Foundation of China [Ref. No. 42430515], General Research Fund project funded by the Research Grants Council of Hong Kong SAR [Ref. No. 18607521], and Humanities and Social Sciences Prestigious Fellowship Scheme by the Research Grants Council of Hong Kong SAR [Ref. No. 38000322], and Strategic Hiring Scheme, The Hong Kong Polytechnic University [Ref. No. P0048587].

Author contributions

David D. Zhang, Qing Pei, and Shengda Zhang initiated the idea. Shengda Zhang and Lebin Wang collected the data and developed the model. Qing Pei, Shengda Zhang, and Mengyuan Qiu did the data analysis. David D. Zhang, Qing Pei, Shengda Zhang, and Mengyuan Qiu wrote the paper. All authors contributed to the editing of the paper.

Competing interests

The authors declare no competing interests.

Ethical statement

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1057/s41599-025-05283-z>.

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