The Diffusion of Epichoric Scripts and Coinage in the Ancient Hellenic Poleis [1]

Yuxian Chen* and Yannis M. Ioannides**

October 13, 2024

Abstract. Little is known about the diffusion of adoptions of alphabetic writing and coinage, in spite of their being among the most significant innovations in history. This paper explores their spatial diffusion in the ancient Hellenic poleis. Using information on dates of adoption by each polis, their locations and geographical characteristics together with imputations of travel times, we estimate the dynamics of adoption and spatial diffusion and find positive spatial spillovers in the adoption of both technologies. We find evidence supporting conformity in the adoption of scripts and deliberate interaction among poleis in the adoption of both technologies. We find the spatial diffusion to be more important than such time-invariant factors as travel network centrality and proximity to potential origins and to mines of precious metals. We find that ignoring spatial factors can cause biases in estimating the impact of the adoption of one technology on the adoption of the other.

* Doctoral student, Department of Economics, Brown University. Yuxian_Chen@brown.edu

---

[1] This version: October 7,2024. Earlier versions of this paper were presented at the Urban Economics Association meetings, CRETE, Clark University, NBER Summer Institute – Urban Economics, BSE Summer Forum 2022 (Geography, Trade and Growth), and CEP/LSE Urban/Regional seminar. Thanks go to Xu Dong, Teddy Glaeser, Gengbin Piao, Nicholas Reynolds, and Zach Sowerby for their help with the data, to Alan Johnston, Jack Kroll and Jacques Melitz for exceptionally useful, thorough and constructive comments and numerous corrections, but also to Marios Angeletos, Panle Jia Barwick, Marcelo Bianconi, Giorgos Bourogiannis, Alain Bresson, John Brown, Alessandra Casella, Aureo de Paula, Yannis Evrigenis, Oded Galor, Ed Glaeser, Matt Kahn, Michael Kosmopoulos, Ch. E. Maravelias, Eoin McGuirk, David Nagy, Dimitri Nakassis, Theodore Papageorgiou, Eleftheria Pappa, Robert Pitt, Giacomo Ponzetto, Louis Putterman, Ferdinand Rauch, Albert Saiz, Kurt Schmidheiny, Enrico Spolaore, Adam Storeygard, Jacques Thisse, Matthew Turner, Etienne Wasmer, Roger Woodard, and Junfu Zhang for useful suggestions, and to Josh Ober and Peter Van Alfen for data and many related suggestions and comments. We are grateful to Christopher Barnett, Uku-Kaspar Uustalu, Carolyn Talmadge and the other members of the Tufts Data Lab team for the construction of the data set for sailing times across the coastal segments of the Mediterranean and the Black Seas. We are also grateful to Sotiris Kampanelis and his coauthors for lending us their data on Phoenician sites. Thanks also go to Stelios Michalopoulos, whose contribution to preliminary research leading to a companion piece, Chen, Ioannides and Rauch (2022), titled "Asymmetric Trading Costs and Ancient Greek Cities," was an important part early in this research effort. Comments by Jan Bakker and Claudia Steinwender at CEPR Conference ERWIT/CURE, Turin, 2023, are gratefully acknowledged. The usual caveats apply.

This research was entirely funded by Brown University and Tufts University resources.

** Professor of Economics, Tufts University. 177 College Avenue, Medford, MA 02155. +1 617 627 3294. Yannis.Ioannides@tufts.edu. (Corresponding author).

JEL codes: F1, N7, N9, N12, R12, B55

Keywords: Hellenic scripts and alphabets, Greek alphabet, diffusion of innovations, weighted directed networks, centrality, ancient Hellenic poleis, economic geography, coinage issue, spatial diffusion of innovations.

1 Introduction

The humanities literature is undecided to this day as to the precise geographical origin and date of the emergence of the Greek alphabet. It is widely accepted that it originated in the West Semitic script, and thus became known in the classical Hellenic world as Φοινικήια Γράμματα [*Phoenician Letters*]. According to Herodotus, 5.58:

> *"These Phoenicians who came with Cadmus* [the mythological founder of Thebes] *and of whom the Gephyraeans were a part brought with them to Hellas, among many other kinds of learning, the alphabet, which had been unknown before this, I think, to the Greeks. As time went on the sound and the form of the letters were changed. [2] At this time the Greeks who were settled around them were for the most part Ionians, and after being taught the letters by the Phoenicians, they used them with a few changes of form. In so doing, they gave to these characters the name of Phoenician, as was quite fair seeing that the Phoenicians had brought them into Greece.1 [3] The Ionians have also from ancient times called sheets of papyrus skins, since they formerly used the skins of sheep and goats due to the lack of papyrus. Even to this day there are many foreigners who write on such skins."*

Whereas this passage is widely cited, archaeological evidence referring to the Greek letters as Phoenicians predates Herodotus; see Lilian H Jeffery and Morpurgo-Davies (1971). Modern scholarship recognizes that it was probably Greek speaking users of the West Semitic script who developed what came to be known as the Greek alphabet.[2] They did so by mainly

---

[2] We refer to“Scripts” rather than Alphabets in deference to L. H. Lilian Hamilton Jeffery (1961), whose

adopting Phoenician consonants whose phonetic values did not exist in the Greek dialect of the originator and by assigning Greek vowel values to those leftover consonant symbols [Lilian Hamilton Jeffery (1961)]. For more details, see the Supplementary Appendix Online. As Woodard puts it, those writers (perhaps even scribes) "thus created the first alphabetic writing system to represent systematically both consonants and vowel sounds" [Woodard (1997), p. 135-136, and fn. 7]. It is the diffusion of the many variants of the alphabet that were established which constitute the focus of this paper. They are referred to here as *epichoric*, that is local scripts, in deference to the classical scholarship [Lilian Hamilton Jeffery and Johnston (1990)]. While there is widespread agreement on the origin of the scripts, the exact process through which they spread is not known [Cross (1989)].

Issue of coinage by Hellenic poleis, which are typically referred to as city-states, constitutes another important innovation whose diffusion is associated with conceptual issues similar to those of scripts. It diffused in the ancient Hellenic world largely later than the alphabet. A *tacit agreement* is at the heart of standardizing coins and stamping them with "symbols" reminiscent of the poleis that issued them and later on of their rulers, characteristic products or deities, indeed a revolutionary invention, that was endorsed by the authority of the polis that issued it [Schaps (2004); Schaps (2007)]. Quantities of precious metals (hoards or bullion) had been used in effect as commodity money, prior to coinage. Yet the accumulation of hoards of precious metals might not have originally been perceived as money as such.[3]

The spread of coinage began with coins made of electrum, an alloy of gold and silver that occurs naturally in the area of Mount Tmolos and could be panned out of Paktolos River in ancient Lydia (east of modern Izmir).[4] Electrum coinage appeared "somewhere between 650 BCE and 550 BCE in Asia Minor, at the interface between the Greek and the Asian world"

---

digitization we rely on.

[3] The reasons coins were issued in the first place is also debated by the literature, but is not discussed here. In this connection, see Bresson (2005)

[4] "And of all men whom we know, the Lydians were the first to mint and use a coinage of gold and silver; Herodotus. *Histories.* Book I. 94. See Kroll (2010)

[Van Alfen and Wartenberg (2020)].[5] Because of the naturally occurring differences in the content of gold and silver, when used in ancient coinage electrum "was almost always in a carefully controlled artificial mixture" which suggests a level of technological sophistication [Kallet and Kroll (2020), p. 158]. A certification process together with trust was necessary to make those coins able to travel and be negotiable as money [Melitz (2017)].[6] As Hodos puts it, "it was the idea of coinage, rather than the Lydian coin system itself, that traveled where coins were used for local and regional purposes" [*ibid.* p. 70]. From around 610 BCE on, coinage and associated standards diffused throughout the system of Hellenic poleis.

Both scripts and coinage are likely to have been huge technological shocks at the time. Linear B, a syllabic script for an archaic version of Greek, was used in some parts of Greece down to 1400 BCE. It disappeared around 1200 BCE along with the Bronze Age administrations that seem to have used it. The "Dark Ages" that followed for hundreds of years were not associated with writing until the emergence of epichoric scripts. For coinage, while bullion and other form of unprocessed precious metals had been used for transactions and as store of value [Kroll (2013)], the emergence of coinage, money, was an important and completely new technology that had additional advantages such as lowering transaction costs and facilitating tax collection. The interest of local rulers were served by both innovations. E.g., some of the earliest written records preceding alphabets are in the form of tablets resembling modern spreadsheets, that seem to record transactions, such as those from ancient Uruk, Iraq [Robinson (2009), p. 10-12]. The Linear B tablets also record transactions, mainly in the form of interactions with the state pertaining to tax revenue, assignment of contract work or military conscription. Issue of coinage and the need to fight counterfeiting was critical for the ability of rulers in ancient Asia Minor, especially Lydia, to finance the operations of the state during the study period.

---

[5] "It was continued and emulated throughout the Greek world (though not, at first, the Asian world), but with a substantial change: from [King] Croesus onward, coins were made of either gold or silver, as a rule practically pure" *ibid.*

[6] Cahill et al. (2020) discuss evidence that early electrum coins from Sardis were not minted from Paktolos River electrum, which mitigates in favor of regulation of the gold content of coinage. We owe this reference to Jacques Melitz.

This paper employs previously unutilized data on the dates of adoption of scripts[7] and issues of coinage by different poleis[8] as technological innovations, supplements them with data on archaic and classical Hellenic poleis [Hansen and Nielsen (2004)] and merges them with microgeographic information and imputations of travel times across poleis. It uses these data to test theoretical predictions of a spatial-game theoretic model about the spatial evolution of script adoptions by Hellenic poleis during the early historical era. It also uses predictions of a companion empirical model for the issue of coinage by poleis in order to conduct an empirical analysis of the diffusion of coinage as an innovation across Hellenic poleis during roughly the same historical era.

We believe it is important to analyze in a single paper the diffusion of the two technologies, namely scripts and coinage for two main reasons. First, those two technologies were not only critical innovations in the history of technology, but also developed and diffused in the same institutional setting, namely the ancient Hellenic world, ancient Greece for short, and within the same historical era. Thus, it is interesting to see the similarities and differences in the gradual adoption processes of the two technologies. The diffusion of scripts started in the late eighth century BCE and continued through the fifth century. Coinage was first issued in the late seventh century BCE and continued thereafter beyond the conquests by Alexander the Great at the end of the fourth century BCE. Those conquests were followed by many new states issuing coinage and into the late antiquity, by which time it was no longer an innovation. Second, while the overall institutional setting is similar, the diffusion of scripts happens on average one to two centuries earlier than coinage. This allows us to use these two technologies as a setting to study the effect of adopting one technology on that of the other, and to explore any biases emanating from ignoring spatial factors.

Although the diffusions happened within the same historical era, the respective processes differ with respect to some key details. Adoption of mutually intelligible scripts confers

---

[7] To the best of our knowledge, writing as a technological improvement is first recognized in the economics literature by Ashraf and Galor (2011)

[8] The paper follows the convention in the classics literature and adopts transliteration of Greek spelling, so that *poleis* is plural for *polis.*

benefits to all parties but possibly not uniformly, much like a non-rival public good though with little resource cost. In contrast, issue of coinage requires precious metal and can thus induce competition and free-riding. For scripts, being close to previous adopters is likely to be purely beneficial — getting more knowledge about the technology when more neighbors use a script, a communication tool and non-rivalrous public good with no negative externalities. A positive externality could well be present when one's neighbors also use a script. There can be larger gains from adopting a script which can be used not only domestically, but also in communicating with neighbors.[9] Adoptions of scripts by scribes and educated elites mark the beginning of literacy.

For coinage, being close to previous adopters accords a polis a complex set of tradeoffs. Unlike scripts, striking coinage required not only familiarity with the idea — not a trivial matter according to classics literature [Seaford (2004)] — but also possession of the respective technology and access to sources of precious metals. There were few known mines of precious metals around the Mediterranean, and therefore many poleis needed to obtain precious metal through interpolis trade. While coinage was a huge innovation that facilitated within-polis and interpolis trade, as we discuss further below, precious metals in the form of bullion were used prior to the emergence of coinage. Thus it is unclear how having more neighbors as coin issuers would affect the cost of obtaining precious metal. Besides, if use of coinage is beneficial but the production of it is costly, as Melitz (2017) elaborates, then a polis may "free ride" by using coins issued by other poleis or joining a coinage (monetary) union. Geographical locations that are advantageous with respect to availability of mines and trade may generate a region of dominance, which may be traded off against surrendering "coinage sovereignty." Coinage issue may be prone to conflicts giving rise to network externalities and spillover effects, rendering the sign of the effect ambiguous.

Apart from different potential externalities, script and coinage also differ in terms of a

---

[9] While there are many scripts recorded in our data, the main stream thought among the scholars is that they were developed because of "a slip of the pen" (Johnston (1998)). The various epichoric scripts are quite similar to one another, so that users of one could decipher writing in others.

key detail, that is, exactly where and when their diffusions originated. The invention of coinage, at least in that part of the world, and most likely globally, originated in Sardis, an ancient non-Hellenic city state in Lydia. Whereas the epichoric scripts are known to have derived from the North Semitic script, what is not known with geographic and time precision is where its *adaptation* in the form of epichoric scripts actually first occurred. As we discussed earlier, scholars agree that the adaptation most likely happened once! Since the invention of coinage facilitated transitions[10] of the Hellenic poleis to market economies [Bresson (2005); Schaps (2004)], if indeed the term is appropriate, it is exactly to a better understanding of this urbanization process that the present research agenda also seeks to contribute. The full impact on early urbanization will be taken up in future research.

In our analysis we also consider factors that could have impacts on the adoption of both technologies. Trade is one factor that needs to be taken into account, potentially playing important roles for the adoption of both technologies, both of which do facilitate it. Given the evidence of trade in the ancient Greek world and that the demand for both technologies may have arisen from the needs of trade, it is reasonable to assume that (overall) trade potential would affect the adoption decision for both technologies, apart from the externality across adoption decisions by different poleis. Interpolis trade is facilitated by both script adoption and coinage issue, although not both of them might have been attested to be present at all instances and locations.

Apart from trade, polis size may have been an important factor for effective adoption of both technologies, but its effects might have been potentially different. Learning the letters and expressing the same spoken language in writing eases communication much more cheaply. While knowledge of coinage as an innovation might easily diffuse, its actual implementation in the form of striking coins requires resources for metal processing, production and enforcement against counterfeiting. Polis size and therefore state capacity could potentially matter more for coinage than for script adoption, while both technologies reduce trading costs. That is,

---

[10] "Around 600 BCE, the Greeks were in a phase of transition towards a market economy" [Bresson (2005)].

size could lower per capita cost for both technologies, if their costs of adoption has a fixed component, an effect that could be much less important for scripts.

Connecting our work to the existing literature, as we mentioned earlier, Ashraf and Galor (2011) were the first to consider writing as a TFP shock, though not explicitly its spatial diffusion. Stasavage (2021) examines the spatial diffusion of writing globally from three potential origins, that is, Ancient Sumeria, Ancient China and Mesoamarica, and its role in the emergence of the state. In contrast, the present paper addresses the spatial diffusion of the adaptation of the Phoenician alphabet (itself descending from the North Semitic alphabet), in the form of the epichoric scripts, the various versions of the Hellenic alphabet. The spatial diffusion of several technologies across countries and over time has been studied by Comin, Dmitriev, and Rossi-Hansberg (2013), but only since early 1800 CE. Dittmar (2011) studies the impact of the diffusion of the printing press in European cities from 1500 to 1600 CE. Yet we are unaware of any research even remotely related to the central topics of this paper, that is spatial diffusion of alphabetic writing and coinage in ancient times. Given the fact that both those technologies were ultimately adopted, a key challenge is how we may infer exactly when and how they diffused.

Previewing our results, we note that we confirm several key predictions and also highlight important findings. There exists a positive externality in the spatial diffusion of both script and coinage. We also identify nonlinear effects, supporting conformity behavior for script adoption. The directionality of travel times (which also proxy for shipping times) as distinct from geographical distances allows us to claim a role for deliberate interaction. In terms of relative importance, lagged spatial diffusion is more important than centrality and distance to origins/mines, but less important than local geographical/ productivity variables combined. Polis size has a very large role for coinage but a smaller one for script. As for the effect of time-invariant factors, centrality in the travel network is positively correlated with script adoption but negatively correlated with coinage. Being closer to mines of precious metals is associated with earlier coinage adoption. Proximity to potential origins of scripts in the

Hellenic world and to Phoenician colonies have no effect when spatial diffusion factors are included. Script adoption does have positive effects on coinage issue, but failure to account for spatial factors in the analysis produces noticeable bias.

In the remainder of this paper, Section 2 presents the data and Section 3 starts out with conceptual motivation for a number of key economic concepts that clarify our empirical variable definitions. It then continues with our estimation results, specifically with estimations of the spatial evolution of script adoption and coinage issue, of the roles of key time-invariant factors followed by comparisons of their relative importance in explaining the spatial diffusion of the two technologies. An examination of the statistical interdependence of those outcomes completes the empirics. Section 4 concludes. Figures and tables of empirical results are given at the end. Supplementary data and empirical results are given in a Online Supplementary Appendix, which is not to be published. Additional institutional and historical facts, which are also not to be published, are provided in that Appendix.

2 Data

2.1 The Poleis Data

We rely extensively on the Polis Project data from http://polis.stanford.edu/, whose digitized information comes from *the Inventory of Archaic and Classical Poleis* [Hansen and Nielsen (2004)], a detailed compilation of the entirety of the archaeological and historical data for 1037 archaic and classical Hellenic cities by the Copenhagen Polis Centre. Some of the data were digitized by Josiah Ober and his team of Stanford and Oxford scholars. Figure 1a shows a map of poleis used in this paper. While poleis did trade with non-Hellenic city-states and sites — including very distant ones; see Quinn (2024) — the center of the action for the adoption of Hellenic scripts and issues of coinage were Hellenic poleis, and therefore our emphasis on them does not bias our estimations.[11]

Important variables that we use from these data include: size, fame, and geographical coordinates. There are other interesting variables such as colonies and colonizers, participation in the Delian League, and *Koinon* (participation in a regional federation). Due to endogeneity concerns they do not play a central role in our discussion.

Size is a complex matter, as Hansen and Nielsen discuss [*ibid.* 70–73], and is thought of as a proxy for polis influence or territory; it is defined categorically in terms of ranges of polis territory: $[0-25), [25-100), [100-200), [200-500), \geq 500$ km^2 [*ibid.* p. 7] and is available for 635 poleis [*ibid.* p. 71]. There exists a second variable that is intuitively close to size, called fame in the data, which is defined as the number of columns of text in Hansen and Nielsen (2004). It proxies for prominence of a given polis. Fame is available for all poleis and we use it to predict size for poleis with no size data. Of the 1037 poleis in *ibid.*, 143 poleis lack location information. Since our analyses rely heavily on such information, our quantitative analysis will be restricted to (at most) the 894 poleis with known locations.

We use the available geographic coordinates to merge the poleis data with such micro-geographic information about their location as ruggedness, malaria index, temperature, precipitation, and elevation. The ruggedness index is from Nunn and Puga (2012), the malaria index is from Kiszewski et al. (2004), the crop suitability data are from Zabel, Putzenlechner, and Mauser (2014), and temperature, precipitation, and elevation are from WorldClim.[12]

2.2 Script and Coinage Data

The data for script adoption come from the *Poinikastas* Database, a digitization of the entire archive underlying Lilian Hamilton Jeffery and Johnston (1990).[13] Our data set includes adoption times by poleis for 174 epichoric scripts. Since some scripts are associated with the regions where poleis lie, 622 poleis may be matched with at least one script. Among them,

---

[11] Also, even when we consider the Phoenician colonies in section 3, we show that distances to Phoenician colonies has little impact on script adoption conditional on distances to sites of potential origins.

[12] https://www.worldclim.org/data/worldclim21.html.

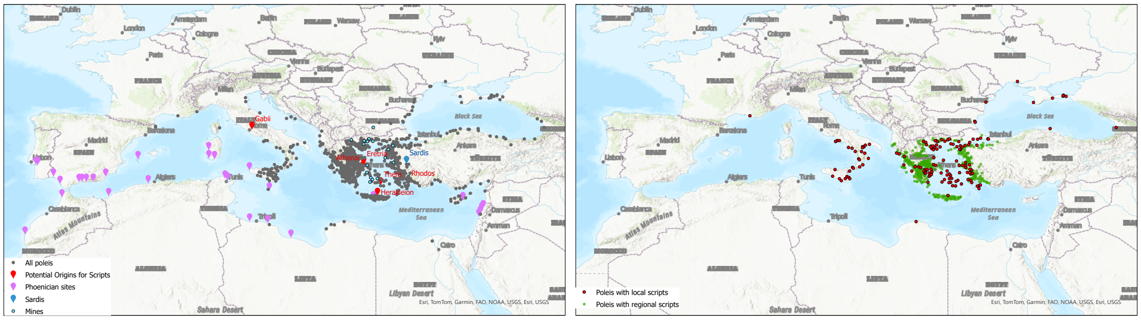
[13] http://poinikastas.csad.ox.ac.uk/

128 poleis are directly matched with a script, that is, not via their regions. The dates of attested adoption of epichoric scripts range from 725 BCE to 416 BCE. Figure 1b shows the location of poleis with scripts: red dots indicate poleis directly matched with a script, green dots poleis matched with a regional script.

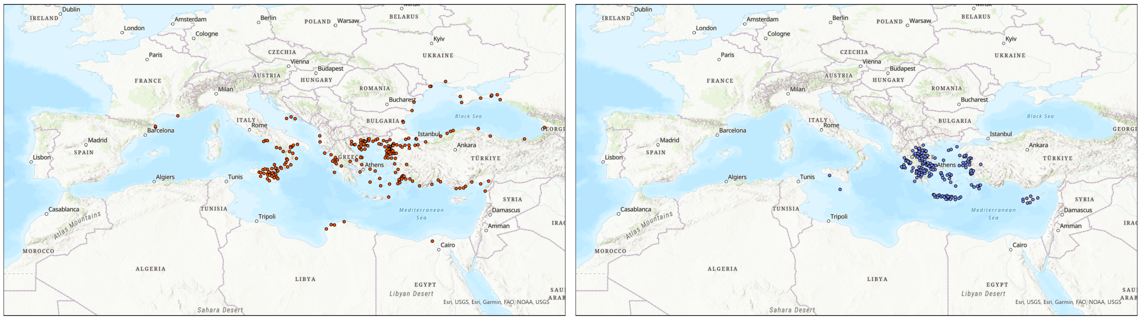
Our data on the times of first issue of coinage are taken from two sources. One, which is available in the original database of the Stanford Polis Project, records time of issue by century; the second, which we coded manually ourselves, uses the more detailed information available in Hansen and Nielsen, *op. cit.,* either according to attested approximate year or approximation by interval midpoints. Silver coinage is the most prevalent form, with 339 vs. 187 observations, from the first and second sources respectively, followed by 284 vs. 148 for bronze. Figure 1c and Figure 1d show the locations of poleis that issued coinage for which precise and imprecise dates are available, respectively. Gold and electrum coinage are much rarer. In our data 21 poleis issued gold coins and 9 poleis issued electrum coins. As we discussed earlier, the numismatics literature has concluded that electrum coins were the first ones to be issued; see Hodos (2020), Ch. 3, Kallet and Kroll (2020), and Van Alfen and Wartenberg (2020). In this paper, we do not differentiate between the types of coinage and consider only the earliest date of coinage issue if a polis issued multiple coin types in its history. A histogram showing the number of adopters by dates in years is given by Figure 2. In the online Appendix, we report the aggregate adoption curves for script adoption and coinage issue.

The adoption processes of both technologies are censored. The script adoption process is censored at 403-402 BCE, when Athens legislated the adoption of the Ionic script [D'Angour (1999)], which became standard thereafter. The coinage process is censored at around 250 BCE. Especially after Alexander the Great's conquests in the late fourth century BCE and emergence of many new states, coinage became ubiquitous. Still, not all poleis are attested to have issued coinage. Thus, when analysing the role of the time-invariant variables in section 3.2.3, we use survival analysis, which accounts for both the extensive and intensive margin, as robustness check for both technologies. The results confirm that our main specification is robust.

Figure 1: Maps for the Poleis



(a) Poleis, Phoenicia sites and origins (b) Poleis with scripts



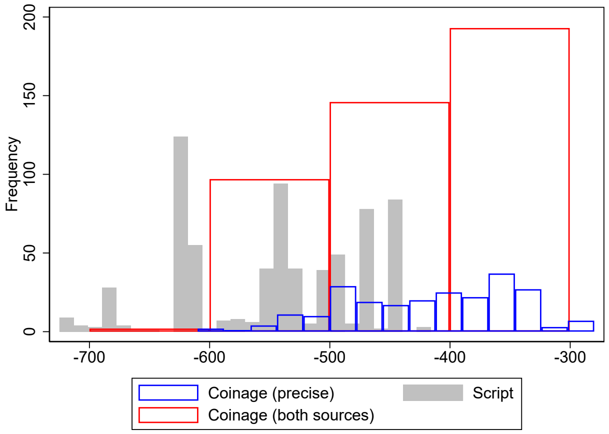
(c) Poleis with precise coinage dates (d) Poleis with imprecise coinage dates

Notes: Figure 1a show the locations of poleis (gray dots), documented origins for scripts (red markers), Phoenicia sites (light blue markers), and mines (blue dots). Figure 1b shows the locations of poleis with local script (dark red dots) and regional script (light blue dots). Figure 1c and Figure 1d show location of poleis with coinage and for which we know the more precise coinage dates, and poleis with coinage but for which we only know the coinage date in century, respectively.

2.3 Travel Times

Travel times across poleis are crucial for our analysis. Spatial diffusion measures, trade potential, and proximity to potential origins of diffusion all depend on them. Our travel times consist of two additive components. One component is the pairwise travel times across coastal sites around the Mediterranean and Black Seas. With the help of the Tufts Data Lab team, we construct 2737 evenly spaced segments that cover the entire coastline of the

Figure 2: Histograms for Dates of Script Adoption and Coinage



Mediterranean and Black Seas. The sailing times for all coastal segment midpoint–pairs are based on wind speeds and parameters from Whitewright (2011). The coastal midpoints are about 15km apart. Further details are given in the Appendix of Chen, Ioannides, and Rauch (2022).[14]

A second component is constructed from overland travel times in the form of walking times and are based on the `Human Mobility Index` [Özak (2010); Özak (2018)]. Using Özak's cost surface we compute the overland travel times as the least-cost paths for all polis pairs and the times between each polis and their nearest coastal sites.[15] Thus, we account for the differential costs of shipping by assuming travel costs, in hours, between inland points a and b in the form:

$$d_{a,b} = \min\{\gamma * \text{walking }_{a,b}, \gamma * \text{walking }_{a,A} + \text{sailing }_{A,B} + \gamma * \text{walking}_{B,b}\}, \tag{1}$$

where parameter γ adjusts upwards the cost of overland travel relative to maritime travel;

---

[14] The wind data come from a NASA site: https://podaac.jpl.nasa.gov/dataset/CCMP and was averaged over all available years (1987 to 2011).

[15] Overland shipping was known to be much costlier than maritime shipping; as Bresson (2016) Ch. 3, p. 80, states: "Clearly, the cost of overland transport was much higher. A relationship of 1 to 40 has been proposed, based on prices mentioned in Diocletian's *Edict on Maximum Prices* in the late Roman Empire". Masschaele (1993) suggests a ratio of 8:1 for land versus water transport for fourteenth-century England.

(A, B) denote coastal segments nearest poleis a and b, respectively. For results reported in this paper, we use $\gamma = 5$. Alternative traveling cost parameter values $\gamma = 10$ and $\gamma = 20$ yield qualitatively similar results with those of $\gamma = 5$ and are thus not reported.

3 Empirical analysis

3.1 Spatial Evolution of Script Adoption and Coinage Issue Decisions

In this section, we explore the potential spillover effects of adoption decisions for both alphabetic writing, referred to as script adoption, and coinage issue, linked to a polis' neighbors. There are several ways to think of why there would be such spillover effects from preceding adoptions. A priori, such adoptions could be evidence of "exogenous" diffusion of knowledge, or of deliberate decisions by poleis motivated by desire for conformity. Indeed, both those possibilities are featured in the diffusion literature, such as Young (2009). However, apart from such positive spillovers as commonly considered in the diffusion literature, there could in effect be negative spillovers in the form of a free rider effect. That is, a polis could "free-ride" on coinage issued by other poleis instead of issuing coinage itself, provided that it could acquire coinage. Finally, omitted variable bias could also be responsible for observed correlations in adoption decisions of neighbors.

Exogenous diffusion of technology is the case where a beneficial technology diffuses, perhaps because information about its actual value is initially unknown and then observed when neighbors adopted. If a polis sees its neighbors adopting it to good effect it may follow suit. But there are no deliberate polis actions such as greater efforts to obtain more information. Under such a scenario we should expect a positive and at a minimum a linear effect of the proportion of neighbors that have adopted the technology. This is known as the Bass model (Bass (1969)), or alternatively, the contagion model of Young (2009). Expressed in terms of

$p(t)$, the proportion of current adopters, we have:

$$\frac{\dot{p}(t)}{1-p(t)} = \gamma + \lambda p(t). \tag{2}$$

That is, the rate of new adopters as a share of non-adopters, the l.h.s. of the above, is a linear function of $p(t)$.

A second possible source of positive spillovers is conformity. It is present when the payoff of adoption depends on whether such adoptions are sufficiently prevalent among a polis' neighbors inducing it to adopt. Young (2009) terms this possibility social influence or social learning, and argues that a polis adopts when the proportion of adopters exceeds a threshold level. In such a case, the relationship between the proportion of adopters and the probability that a polis adopts would imply an inflection point near the threshold.

All these possibilities may be accommodated, in a discrete time setting, as special cases of the model of Proposition 6, Konno and Ioannides (2019). That model is a generalization of spatial logit models where agents interact with their two nearest neighbors to the case of many agents.[16] The probability that a polis adopts a technology, conditional on the actual adoption state, $\tilde{S}_{\nu(i),t-1}$, of its neighbors, $\nu(i)$, in the preceding period, $\mathrm{D}_{i,t} = \mathcal{A}|\tilde{S}_{\nu(i),t-1}$, is a hyperbolic tangent function of a linear function of adoption status of a polis' neighbors in the preceding period. That is:

$$\text{Prob}\left\{\mathrm{D}_{i,t} = \mathcal{A}|\tilde{S}_{\nu(i),t-1}\right\} = \frac{1}{2}\left[1 + \mathcal{A}\tanh\left(\beta\sum_{j\in\nu(i)} B_{ij}\tilde{S}_{j,t-1} + \beta h\right)\right], \mathcal{A} \in \{-1, 1\}. \tag{3}$$

where $\mathcal{D}_{i,t}$ is the adoption decision of technology $\mathcal{D}$ for polis i in time t. The adoption decision is either $\mathcal{A} = -1$, not to adopt, or $\mathcal{A} = 1$, to adopt; β is the payoff-responsiveness parameter, h the intrinsic value of adoption, and B_{ij} is the strength of the interaction coefficient. For conformity, $B_{ij} > 0$. [17]

---

[16] The model implies an adoption probability either associated with a cooperative strategy in a prisoner's dilemma game, or with a Pareto efficient strategy in a cooperation game, respectively.

[17] While multiple equilibria may exist (see Brock and Durlauf (2001) Proposition 2 and Ioannides (2013),

The above spillover mechanisms are motivated by the benefits of adoption. However, and especially for a technology whose adoption requires physical resources, the cost of adoption can be affected by geographical factors as well. Intuitively, one may think that resources would be easier to get from other adopters, because they have acquired that resource for adoption themselves. Indeed, for coinage issue, resources were required by ancient Hellenic poleis. Acquisition of precious metal, such as silver and gold, but also copper, was critical as there were very few mines around the Mediterranean and such resources had to be procured. Nevertheless, in the case of coinage issue, a polis did not necessarily have to obtain precious metal from neighbors. As we mentioned earlier, prior to the invention of coinage, metals in the raw form (or bullion) were used for trade and transactions as well. In some instances, coinage and bullion even coexisted. Thus, even at poleis which had not issued coinage, metals were available and could be used to strike coinage [Kroll (2013)]. Issue of coinage removed the provision of money from the private sphere and placed it, like weights and measures, under the authority and the legal protection of the state. Therefore, we do not think access to resources is a mechanism for how the proximity to previous adopters have an effect on coinage.

Even if we rule out direct ways for spatial spillovers to reflect the cost of adoption, there is another way for spatial spillovers to affect the cost-benefit trade-off that we think may matter. In the case of coinage, a "free rider" effect is possible. As Melitz (2017) underscores, coinage is beneficial because it serves the traditional functions of money, namely unit of account, medium of exchange and store of value, but is costly to issue. Therefore, a polis may "get by" using coins issued by other poleis instead of striking its own. This would in effect be"free riding" on coinage issued by other poleis. A polis could earn such coinage by trading or by other means, including violent ones like plunder and looting. Such an instance would imply a negative effect from the adoption decisions of other poleis on a polis' own decision to issue coinage: B_{ij} may be negative. A "free rider" effect would be rational when

---

Ch. 3), their likelihood diminishes when the intrinsic value of adoption is high, which is likely to be true in our case. See more discussion in our online appendix.

the coinage is costly to issue, but there is also the possibility for coinage to serve as a source of seigniorage. Therefore, whether a free rider effect is present is an empirical question. As script adoption would not require much in terms of resources, these arguments apply to coinage.

Finally, in addition to genuine spillover effects, observed spatial spillover patterns may originate in omitted variable bias. While it may well be the case that the adoptions are actually determined by polis size, an additional and not mutually exclusive "effect" might be present. That is, the properties of the urban hierarchy may be such that make a polis' own size be correlated with the proportion of its larger neighbors. In the absence of a direct effect of size this possibility would imply spurious correlation with the proportion of neighbors that have adopted. We can account for this by including a polis' own size as a control variable.

Yet another possibility is presence of spatially correlated shocks. For example, if in some period a region experienced very beneficial climatic variation, poleis there would have grown and accumulated more wealth, and therefore found it advantageous to adopt a script. In that case, we would expect nearby poleis to behave similarly because of spatially correlated shocks rather than spatial spillovers. We can control for this source of spatial correlation by distinguishing between travel distance and geographical distance ("crow-flies" distance) between poleis, and by also controlling for proximity in terms of the latter.[18] Geographical proximity is a more appropriate control for spatial correlation in climatic conditions. Arguably, having controlled for geographical distance, travel distance only matters as an impediment to interactions across poleis.

Our arguments so far have treated coinage issue as an instance of technological adoption. It is of course possible to study it by embedding it in a theoretical model for coinage. However, given our data, there are no additional testable predictions from such a model. We thus provide more discussion for it in the online appendix.

In order to estimate spatial spillover effects from neighbors, we organize our data into a

---

[18] There exists moderate variation in the respective variables that may justify this claim; the correlation between the "crow-flies" distance and our travel distance measure is 0.71.

panel structure. To capture spatial spillover effects we define the variable "weighted proportion of neighbors that have adopted" as of period $t-1$, $\mathrm{MA}(\mathcal{D}_{i,t-1})$:

$$\mathrm{MA}(\mathcal{D}_{i,t-1}) = \frac{\sum_{k \in Adopter_{t-1}} 1/\tau_{ki}}{\sum_p 1/\tau_{pi}}, \tag{4}$$

where $Adopter_{t-1}$ is the subset of poleis that have adopted by time $t-1$. This is essentially a measure of market access to previous adopters, suitably scaled by polis i's overall market access. It may also be interpreted as the weighted proportion of adopters among polis i's neighbors, with the neighbors being *all* other poleis and the weights being inverse interpolis distances.[19] Clearly, $\mathrm{MA}(\mathcal{D}_{i,t-1}) \in (0,1)$.

This scaled market access measure exhibits several advantages. First, it has a spatial attenuation property in that it assigns smaller weights to adoption by poleis further away. Second, it allays some of the recent concern about market access being correlated with overall location; see Borusyak and Hull (2023). This variable does not need to be recentered, because if we compute the mean of multiple placebo draws for $\mathrm{MA}(\mathcal{D}_{i,t-1})$ assuming random adoptions, it is almost constant across poleis and equal to the proportion of adopters.[20] Third, this measure by being defined as a weighted proportion of neighbors that have adopted matches the formulation in Bass (1969) and the contagion model of Young (2009). The variables entering our estimations, and in particular $\mathrm{MA}(\mathrm{D}_{i,t-1})$, are first defined in terms of average costs over *From* and *To*. We then explore the significance of asymmetric costs by computing $\mathrm{MA}(\mathrm{D}_{i,t-1})$ alternatively with *From* and *To* costs.

Given the proposed mechanisms above, we estimate linear, hyperbolic tangent and quadratic specifications with respect to $\mathrm{MA}(\mathcal{D}_{i,t-1})$, market access to preceding adopters. The hyperbolic tangent specification is implied by our model of technology adoption and is estimated with maximum likelihood methods. Quadratic specifications are commonly used to capture

---

[19] We can see this from $\frac{\sum_{k \in Adopter_{t-1}} 1/\tau_{ki}}{\sum_p 1/\tau_{pi}} = \frac{\sum_q \mathbb{1}\{Script_{q,o\leq t}\} 1/\tau_{qi}}{\sum_p 1/\tau_{pi}} = \sum_q \mathbb{1}\{Script_{q,o\leq t}\} \frac{1/\tau_{qi}}{\sum_p 1/\tau_{pi}}$.

[20] Our results barely change even if we control for the mean and standard deviation for 500 placebo $\mathrm{MA}(\mathcal{D}_{i,t-1})$.

nonlinearity because they are easy to estimate. If a free rider effect is present, we should see a negative coefficient for $\text{MA}(\mathcal{D}_{i,t-1})$ in any of the specifications employed by the present study, which we summarize in section 3.2 below. If the exogenous diffusion of knowledge is dominant, we should see a positive linear effect without significant nonlinearity. If conformity is dominant, we should see a positive sigmoid effect.

Therefore, the estimation equations corresponding to (2) and (3) are as follows:

$$\mathcal{D}_{i,t} = b_0 + b_1\text{MA}(\mathcal{D}_{i,t-1}) + b_2\left(\text{MA}(\mathcal{D}_{i,t-1})\right)^2 + \mathcal{X}_i\boldsymbol{\beta} + \text{Period}_t + \epsilon_{it}; \tag{5}$$

$$\mathcal{D}_{i,t} = a_0 + 0.5\tanh\Big(c_1\text{MA}(\mathcal{D}_{i,t-1}) + c_0\Big) + \mathcal{X}_i\boldsymbol{\beta} + \text{Period}_t + \epsilon_{it}, \tag{6}$$

where $\text{MA}(\cdot)$ is defined above, $\mathcal{D}$ is a binary variable denoting adoption at the respective time period of either script or coinage, and $\mathcal{X}_i$ is a vector of time-invariant local productivity variables, such as ruggedness index, malaria index, precipitation, temperature, elevation, and crop suitability. We also control for spatial factors that can potentially have effects. First, we control for proximity to potential origins of the diffusion of scripts or coinage and to mines of precious metals. Consider the case where distance to mines makes it more likely for a polis to issue coinage. Then if a polis is close to mines, so are its neighbors, and both a polis and its neighbors would find easier to issue coins. We would thus observe a higher distance-weighted proportion of neighbors that have adopted and a larger probability of coinage issue. To avoid such omitted variable biases, we control for the distance to origins variables directly. Second, we also include measures of centrality in the travel network. The argument would be similar as above: if a polis is centrally located its neighbors would be also relatively centrally located. Thus if centrality has an effect, it would affect both the outcome and the distance-weighted proportion of adopters. In section 3.1.1 we provide additional arguments for why centrality and the proximity variables should have effects. We note that once a polis has adopted in period t, it is excluded from the analysis in subsequent periods. Period_t denotes period fixed effects. Including them is important: as more poleis adopt scripts over time, the script adopters become spatially denser, and $\mathrm{MA}(\mathcal{D}_{i,t-1})$ will grow larger for all poleis as time goes on. Therefore, inclusion of the period fixed effects makes our estimation "within period." As mentioned earlier, we control for spatially correlated shocks by including terms similar to $\mathrm{MA}(\mathrm{D}_{i,t-1})$ but defined in terms of the geographical "crow-flies" distances.

While the strict prediction from equation (3) yields a coefficient of $\tanh(\cdot)$ of 0.5, as in equation (6), we also seek to estimate it. In the online appendix, we estimate it together with all other parameters with maximum likelihood estimation and its denoted by a_1. Our estimates of a_1 range in $(0.35, 0.49)$, which are reasonably close to our theoretical prediction and baseline specification of 0.5. Thus, in the later analysis, we report results using both 0.5 and 0.364 (for script) and 0.489 (for coinage) as the coefficient of $\tanh(\cdot)$.[21]

3.1.1 Important Control Variables for Spatial Analysis

The empirical analysis in the paper relies on a number of variables that are intended to account for the diffusion of those two technologies across the ancient Hellenic poleis and its determinants within the context of the multitude of interactions that they were subject to. The Hellenic poleis were geographically dispersed. They did share linguistic and cultural similarities, engaged in numerous wars that were punctuated by shifting alliances, and also formed systems of trading polities. Land and sea routes were widely used. Winds and currents made travel times, which were relevant for interaction, fighting and trade, dependent on seasonal weather conditions. The poleis traded among themselves but also with their hinterlands and even with very distant populations and non-Hellenic city states.[22]

---

[21] For coinage, the maximum likelihood estimation cannot converge when size of the polis is included as a control variable. We conjecture two causes: as we will show later, first, the effect on coinage issue of the weighted proportion of neighbors that have already issued is not very sigmoid, thus hyperbolic tangent may not be the best model for coinage; second, the Shapley decomposition suggests that size of a polis explains a very large share of the regression R^2. Therefore when it is included, it is harder to estimate the effects of other variables.

[22] Trade was "ruled" in part by a number of federations, known as *Koinon*. Relatedly, of the several shifting sets of alliances the Delian League was particularly important, best known and longest lasting. It was formed in 478 BCE as a defensive alliance following the second Persian invasion of the Greek mainland, developed into a coinage union and supported the hegemonic role of Athens among the Hellenic city-states

As diffusion of both writing and coinage had a lot to do with trade, it would be ideal to have trade data. Unfortunately we do not, and are therefore forced to rely on proxies for trade potential. Specifically, as we discuss next, one such proxy is travel network centrality. While we eschew here full development of a model we wish to briefly address some conceptual issues that provide motivation for our centrality definition. In spite of limited climatic diversity, one could motivate trade by assuming that goods are differentiated by origin and all poleis trade with all other poleis. Interpolis travel costs and polis locations along with their microgeographic characteristics relevant to productivity define fully the economic geography of the system of trading poleis. We also invoke concepts from network theory in order to express polis centrality within the travel network. While many measures of centrality exist, we employ the right eigenvector corresponding to Perron-Frobenius eigenvalue of the matrix that defines the interpolis travel network.[23] Specifically, if $[\mathbf{T}_{ij}]$ denotes the adjacency matrix as inverse distances, i.e., $\mathbf{T}_{ij} = 1/\tau_{ij}$, then its right eigenvector REV is defined in the usual way (and up to scale). It is a pure measure of connectedness and therefore a measure of interaction. We note that for an adjacency matrix thus defined, its right eigenvector centrality is very similar to the commonly used market access measure and our market access measure, as defined in (4) above and also (7) below.[24] We also use two additional centrality measures, due to Kleinberg (1999), which are particularly appropriate in the case of directional travel costs. Kleinberg's hub and authority centralities perform better than eigenvector centrality for directed networks.[25]

---

until the end of the Peloponnesian War in 404 BCE. Its membership varied between 150 and 300 poleis. On the importance of distant trade, see Quinn (2024)

[23] *c.f.* Bloch, Jackson, and Tebaldi (2019) See also the economic geography model in Allen and Arkolakis (2014), where the right and left eigenvectors of a suitably defined homogeneous linear system characterize a trading economy at spatial equilibrium.

[24] To see this we may write in non-matrix form: $REV_i = \lambda \sum_j (1/\tau_{ij}) * REV_j$. Not surprisingly, right eigenvector centrality and market access measures are highly correlated.

[25] Hub centrality, $\mathbf{e}^{hub}$, is defined in terms of the sum-total for each node of what is "demanded" by the authority side of all other nodes, total exports. Authority centrality, $\mathbf{e}^{auth}$, is defined in terms of the sum-total of what each node "demands" from the hub side of all other nodes, total imports. See also Stachurski and Sargent (2022) for similar interpretations of authority and hub centrality. Hub centrality satisfies $\mathbf{e}^{hub} = \mathbf{T}\mathbf{e}^{auth}$. Hub and authority centrality can be computed as the Perron-Frobenius eigenvector (principal eigenvector) of $\mathbf{T}\mathbf{T}'$ and $\mathbf{T}'\mathbf{T}$, respectively. As in the case of eigenvector centrality, greater values of the components of the centrality vectors that we compute denote greater centrality.

Location in the travel network can affect adoptions in multiple ways. As mentioned previously, proximity to other poleis can affect access to precious metals via trade, but can also imply more competition. On the one hand, the more centrally located poleis have access to a greater number of other poleis and can potentially get precious metals from them. On the other hand, such poleis may be in more densely settled regions and need to compete with a greater number of other poleis in acquiring metal. Centrality can affect adoption in other ways, too. For example, centrality can affect a polis' trade potential and therefore its demand for either technology. It may thus affect polis growth and size and therefore its incentive and capacity to adopt a technology. It follows that the effect of centrality is an empirical question, which we explore in section 3.2.3.

Apart from centrality, proximity to known or potential origins could affect adoption as well. Proximity to sites from where the diffusion of scripts might have originated could also have been a significant factor. We consider the effect of proximity to a set of poleis or sites, which are near to, or coincide with, sites that scholars think are likely to have been where their diffusion in the Hellenic world originated. Specifically, Eretria (and nearby Lefkandi, which is not a polis but a site) is directly linked to early transmission of the Chalkis/Kyme (Euboean) script to the Italian peninsula and so is Gabii (see below); Athens (Athenai) was an early cosmopolitan place, with a lot of cultural and economic activity; Thera is specifically mentioned in the literature; and several poleis in Crete are also mentioned, for which the location of modern Herakleion, not a polis in the relevant period but a harbor, may proxy.[26] Rhodos[27] is one such potential origin in its own right as well as a proxy for coastal sites in the Middle East, including all of the Phoenician city states, and of course sites in Cyprus,[28] which is known to have hosted bilingual communities of Greek and Phoenician speakers, all of which lie to the east of Rhodos. The latter three poleis are attested to have hosted bilingual

---

[26] See Lilian H Jeffery and Morpurgo-Davies (1971).

[27] A polis after 408/7 BCE that was formed by nearby Ialyssos, Kamiros and Lindos via synoecism [Hansen and Nielsen (2004)].

[28] See Woodard (1997), Ch. 7, who argues in favor of a transition from Cypriot syllabaries to the epichoric scripts.

communities of Greek and Phoenician traders. Gabii, a site in Italy, is also attested with the Eretrian script at an early date. In addition, we consider separately the effect of proximity to 30 Phoenician colonies[29] around the Mediterranean, since the Phoenician alphabet is believed to have been the precursor of the Greek alphabet via the epichoric scripts.

For coinage, we consider proximity to and from Sardis, a non-Hellenic city state in ancient Lydia, which is known to have first issued coinage in that part of the world. Following the literature that we have already cited and in addition findings reported by Vaxevanopoulos et al. (2022), we select a number of sites that are attested with evidence of ancient mining of relatively high-quality silver and gold deposits and a number of poleis that are known to have issued coinage early, or were close to known mines of precious metals. These poleis include Amphipolis, Ilion, Lampsakos, Phokaia and Thera. We also use data for several sites with mines that are attested to have been used in the relevant historical period.[30] See Figure 1a for a map with the locations of those sites.

Since the distances from (or to) those sites are highly correlated, it would be problematic to include them as individual regressors. Instead, we propose an aggregate in the style of a market access measure of proximity to or from *all* relevant poleis as a *group*. This measure

---

[29] There exists a genuine difficulty in identifying the significance of sites with evidence of Phoenician presence in the area of interest. Bourogiannis (2021), T. 1, lists 33 sites with Phoenician inscriptions that lie in the territory of modern Greece. Most of them are known major poleis, including 13 entries for Athens and its port Piraeus, 7 for Rhodes and nearby Cos, 3 for Delos (a cosmopolitan sanctuary in the middle of the Aegean), 3 for Eretria and nearby Lefkandi, 3 for Demetrias (Volos), and 1 each for Knossos (near Heraklion, Crete), Stageira (Chalkidiki), Paros and Naxos. The oldest of them are: funerary inscriptions at Knossos and Lefkandi, 9th Century BCE, followed by Eretria, early 8th Century BCE, and then Rhodes early 7th BCE, and Stageira, 6th BCE. Our choice of Potential Origins emphasizes evidence of presence of bilingual communities, as distinct from mere presence of Phoenicians, as elaborated by Bourogiannis (2021).

[30] Drawing from Vaxevanopoulos et al. (2022), the sites are: Antiparos, Asimotrypes (Pangaion Mountain), Lavrion, whose exploitation by nearby Athens in the classical era is credited for Athenian coinage power, Kallianoi (Euboia), Kroussia (Macedonia), Megala Therma (Lesbos), Melos, Olympiada (Chalkidiki), Palaia Kavala, Rodopi Mountain range, Seriphos, Siphnos whose mines are known to have flooded in the classical era but were important source of silver prior to that occurrence, and Thasos. These sites include silver and gold mines.

$\mathcal{H}$ is generically defined as:

$$\text{MA:}\mathcal{H}_i = \begin{cases} \sum_{s\in\mathcal{H}} 1/d_{i,s}, & \text{if } i \notin \mathcal{H}; \\ \sum_{s\in\mathcal{H}\setminus i} 1/d_{i,s} + \max_j\{1/d_{j,i}\}, & \text{if } i \in \mathcal{H}. \end{cases} \tag{7}$$

We note an obvious drawback associated with our use of $\mathcal{H}$ instead of controlling separately for *From-distances* from distinct sites. That is, the aggregation underlying $\mathcal{H}$ does not allow us to identify a possibly *most likely single site* from which the respective innovation, either scripts or coinage, diffused, if indeed there might have been a single such site.

Using (7), we define *MA:Potential Origins*, which includes the six sites as potential origins for script, *MA:Phoenician Sites*, defined over known Phoenician colonies, and *MA:Mines*, defined over poleis close to mines and sites with mines themselves, based on Vaxevanopoulos et al. (2022). We thus test the overall importance of proximity to those groups of sites. For consistency of interpretation, while Sardis is a single variable, we also define *MA:Sardis* as the inverse distance to Sardis, so that for all the proximity variables, a larger value means a greater proximity (shorter distance).

An additional variable that we deem as potentially important is polis size. While size itself is a measure of territory, with details described in section 2.1, it is a proxy for state capacity, which can matter for the adoption for both script and coinage but likely more so for coinage. Adoption of a script is a straightforward technology adoption decision with little implementation costs. Issuing coinage is more involved. State capacity and knowledge of metal technology are much more important and are correlated with size.

We are nonetheless more cautious with using polis size than with centralities and proximities to origin. Size can be more endogenous due to reverse causality as technological adoptions are positive TFP shocks that likely promote growth. Thus, we include centrality and proximity to origins in all specifications but report results both with and without size.

We also consider the potential effect of political economy, in our case the membership in the Delian league and in regional federations (Koinon). It is reasonable to suspect that such memberships may be important for technology adoption via such mechanisms as collaboration and sharing of resources, or common shocks prompting adoption. The Delian League, founded in 478 BCE and dissolved in 404 BCE, dominated the Hellenic world under the hegemony of Athens as a military, economic and coinage union. Regional city-state federations, indicated by Koinon=1, were numerous [MacKil (2013); Economou, Kyriazis, and Metaxas (2015)], with the Peloponnesian League under Sparta's influence being best known. They were looser associations and became unimportant after 300 BCE. Membership in either affected economic interactions whose effects could persist after they became officially unimportant.[31] Again due to endogeneity concerns, we do not include membership in the Delian League and in regional federations in our main specification. Whereas membership in the Delian League was less of a choice and forced on poleis because it mostly reflected geopolitical considerations of Athens in support of its hegemonic role, most the regional federations were more likely outcomes of choice by poleis and thus probably endogenous. Thus, we explore their effect only in the subsection 3.2.3, but we do note that, while not shown, the inclusion of the two variables has minimum impact on the coefficients of MA($\mathcal{D}_{i,t-1}$).

3.2 Estimation of Baseline Hypotheses

Referring to Equations (5)–(6), we may summarize the hypotheses we test as follows: H_0 : *No spatial spillovers in adoption;*

H_1 : *Adoption driven by exogenous diffusion of knowledge;*

H_2 : *Adoption driven by conformity*;

H_3 : *Adoption driven by free rider behavior*;

H_4 : *Adoption driven by correlated geographical shocks*;

H_5 : *Adoption driven by polis size, which displays spatial patterns due to urban hierachy.*

If H_0 is true, we should expect b_1, c_1, and b_2 to be zero; if H_1 is true, we should expect a

---

[31] These less well known associations comprised of several poleis and in some instances other forms of community, and were characterized by the division of sovereignty among the regional government and its constituent communities. They were remarkably widespread, with almost all of mainland Greece and the Peloponnese becoming part of a *Koinon* [MacKil (2013); Economou, Kyriazis, and Metaxas (2015).

positive b_1 but an insignificant b_2; if H_2 is true, we should expect c_1 to be positive, implying that nonlinearity is present; if H_3 is true, we should expect b_1 or c_1 to be negative; if H_4 is true, we should expect b_1, c_1, and b_2 to be zero, and the coefficients for the geographical distance-based counterpart of $\text{MA}(\mathcal{D}_{i,t-1})$ to be significant; if H_5 is true, we should expect b_1 or c_1 to be significant when size is not included and insignificant when size is included.

We conduct the empirical analysis of spatial diffusion of the epichoric scripts by breaking the entire span of available data into centuries.[32] With only few adopters in the late eighth century BCE, we combine observations with those in the seventh century and have: late eighth to seventh, sixth, and fifth centuries BCE, with 213, 214, and 197 observations, respectively. Working in like manner we study the spatial diffusion of coinage issue by breaking the entire length of the study into three periods: late seventh and sixth, fifth, and fourth centuries BCE. The numbers of coinage issuers are 66, 157, and 201, respectively.

Table 1 reports the estimation results with the average distances over both directions as follows. Columns 1 and 2 report estimation results with the linear specification equation (5); columns 3 and 4 those with the hyperbolic tangent specification equation (6), and with the coefficient of $\tanh(\cdot)$ set to 0.5; columns 5 and 6, those again with the hyperbolic tangent specification, but with the coefficient of $\tanh(\cdot)$ set equal to 0.364 (for script) and to 0.489 (for coinage); and columns 7 and 8 those with a quadratic specification equation (5). In all specifications the linear and quadratic terms of the crow-flies distance-based $\text{MA}(\mathcal{D}_{i,t-1})$ control for correlations in climatic conditions. Panel B reports results with polis size being controlled for. We are aware of the potential endogeneity affecting polis size and therefore also report results without it; see Panel A. Interestingly, $\text{MA}(\mathcal{D}_{i,t-1})$ is not significant with the linear specification, for either script or coinage, but it is significant for the nonlinear specifications involving $\tanh(\cdot)$. It is strongly significant in the hyperbolic

---

[32] A major reason for this is data concern. For coinage, we have two sources of data, one in terms of century and one in terms of more detailed years. Organizing the data into centuries allow us to utilize both sources of data. For script, although we do not have two sources of data, we have two types of scripts. One is the individual script and one is the regional script. Unless a polis has its other individual script beforehand, we assume all poleis linked to a region to adopt the regional script at the same time, which is not a strong assumption when the period is a century.

tangent specification for script, but insignificant for coinage. It is significant for the linear term in the quadratic specifications for both script and coinage, but the quadratic term is only significant for coinage; see Column 8, Panel A. This suggests that the quadratic specification may not be the best fit.

While we know the shape of the hyperbolic tangent and quadratic functions in general, it is the behavior in the observed range of $\mathrm{MA}(\mathcal{D}_{i,t-1})$ that matters. We thus plot in Figure 3 the estimated relationship as a function of $\mathrm{MA}(\mathcal{D}_{i,t-1})$ as reported in Table 1. For script, we observe substantial nonlinearity and a significant sigmoid shape with the hyperbolic tangent specification. While the estimated quadratic form seems to have an inverse U shape, we note that the quadratic term is not significant in the regression. For coinage, the plots look more linear or slightly concave. This suggests that a log specification may be better. Thus, columns 9 and 10 report the results with $\mathrm{MA}(\mathcal{D}_{i,t-1})$ in natural log. The log specification yields significant coefficients for both script and coinage. The R^2's for the linear-quadratic and the log specifications are almost the same as those for the respective ones for coinage, despite the fact that the former estimates one additional parameter. For script, we do see a larger R^2 for the quadratic relative to a log specification, suggesting that there is more complicated nonlinearity than a simple concave shape.

We also report the log likelihood and the Akaike information criterion (AIC) values; see bottom of Table 1. Since different specifications estimate different numbers of parameters, we cannot simply compare the log likelihood across columns (but may conduct χ^2 tests). The AIC criterion adjusts for the number of parameters and thus is an alternative criterion to compare the fits of different models. A smaller value of AIC implies a better fit. For script, regardless of whether size is included, smallest AIC is seen with the coefficient of the hyperbolic tangent specification being estimated with maximum likelihood, followed by the hyperbolic tangent specification with its coefficient set equal to 0.5, followed by the quadratic specification, the log specification, and finally the linear specification. For coinage, the values of AIC from the smallest to the largest are: log specification, quadratic

Table 1: Spatial Diffusion: the Impact of Proximity to Previous Adopters

	Linear		0.5*tanh()		0.364/0.489*tanh()		Quadratic		Log	
	(1) script	(2) coin	(3) script	(4) coin	(5) script	(6) coin	(7) script	(8) coin	(9) script	(10) coin
Panel A: With Crow-flies MA(adopter)										
MA($D_{i,t-1}$)	0.914	1.640	8.668***	8.488	11.20***	8.754	5.783**	4.968**	0.537**	0.287**
	(1.251)	(1.081)	(3.232)	(5.864)	(3.954)	(6.531)	(2.721)	(2.030)	(0.264)	(0.121)
MA($D_{i,t-1}$)^2							-6.067	-6.599*		
							(3.954)	(3.887)		
R2	0.19	0.07					0.20	0.07	0.20	0.07
AIC	1359.58	1629.29	1343.95	1629.96	1342.91	1629.96	1345.42	1628.27	1351.95	1626.69
Inflection Pt			0.27	0.11	0.28	0.11				
Panel B: With Crow-flies MA(adopter) and own size										
MA($D_{i,t-1}$)	0.922	1.556	8.630**	6.710	11.29***	6.928	5.352**	3.644*	0.505*	0.196
	(1.225)	(1.033)	(3.564)	(5.058)	(4.360)	(5.551)	(2.640)	(1.993)	(0.257)	(0.122)
MA($D_{i,t-1}$)^2							-5.521	-4.139		
							(3.878)	(3.897)		
R2	0.21	0.18					0.22	0.18	0.21	0.18
AIC	1337.70	1432.61	1323.84	1435.03	1322.25	1435.02	1326.13	1433.26	1331.24	1432.61
Inflection Pt			0.27	0.10	0.28	0.11				
Obs	1151	1499	1151	1499	1151	1499	1151	1499	1151	1499
N(D=1)	410	358	410	358	410	358	410	358	410	358

Notes: Pseudo panel OLS regressions. Columns (1) and (2) are results for regressions linear in MA($D_{i,t-1}$). Columns (3), (4), (5), and (6) are results for regressions with hyperbolic tangent specification. Columns (3) and (4) has the parameter before the tanh($\cdot$) term being 0.5, while columns (5) and (6) has the parameter before the tanh($\cdot$) term being 0.364 (for script) or 0.431 (for coinage). Columns (7) and (8) are results for regressions with quadratic specification. Columns (9) and (10) are results for regressions with MA($D_{i,t-1}$) in natural log. In all specifications, the linear and squared terms of the MA($D_{i,t-1}$) measured in terms of crow-flies distances are controlled for. Panel A and B are similar specifications, except for that Panel B additionally control for the size of the polis. Eigenvector centrality, geographical variables including ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability, as well as proximity to origins (for script regressions) to origins/mines (for coinage regressions) are also controlled for but are not shown to save space. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

specification, the linear specification, and hyperbolic tangent specification with previously estimated coefficient, hyperbolic tangent specification with 0.5 as its coefficient, when size is not controlled for; or log specification, the linear specification, quadratic specification, hyperbolic tangent specification with previously estimated coefficient, and hyperbolic tangent specification with 0.5 as its coefficient. These results when combined with the plots suggests that the effect of $\mathrm{MA}(\mathcal{D}_{i,t-1})$ for script is most likely sigmoid, and for coinage most likely concave.

We conclude that spatial spillovers exist for both script adoption and coinage. The fact that the coefficients barely change with and without polis size as a control variable rejects the spurious spatial pattern due to size hypothesis. Besides, the spillovers are mostly positive, suggesting that free rider behavior, if it might have been present at all, had limited effects. We also note nonlinearities in the effects. For script, the sigmoid effect supports the conformity hypothesis: the inflection point is estimated to lie in the range (0.27–0.28). For coinage, the effect is concave and marginally diminishing.

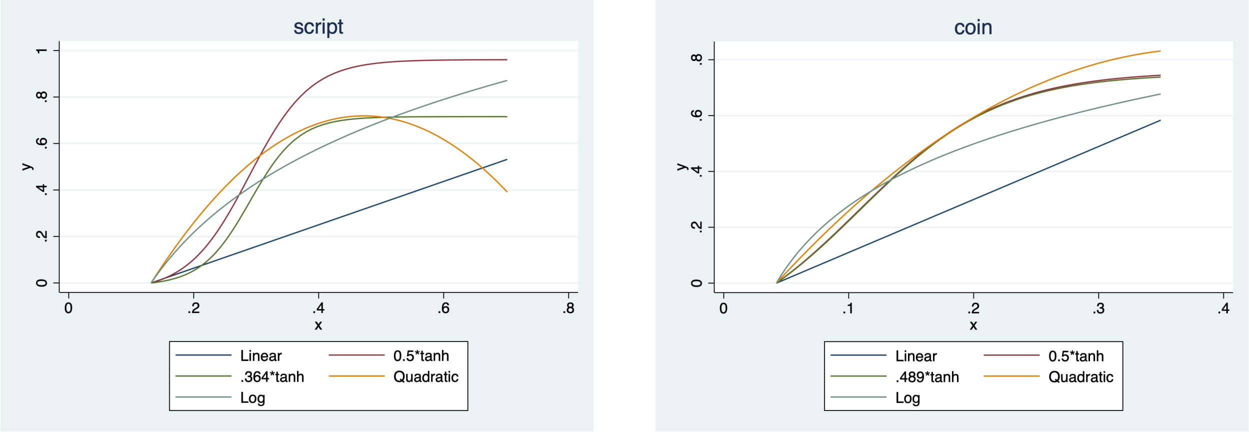
3.2.1 Asymmetric Travel Costs

As discussed earlier, we proxy travel costs by means of combined walking and sailing times, with the latter being affected by winds and currents and thus directional. In the results reported in the preceding section, we use the average cost over both directions, that is, from a polis i to polis or site j, and from polis or site j to a polis i. Next we utilize the full data in order to investigate the possible significance of asymmetry.

Table 2 reports results with the counterpart of the above analysis where instead of using the average costs of *To* and *From* poleis the estimations are conducted separately with traveling costs *From* a polis i (hereafter referred to as *From-distance*) and *To* a polis i (hereafter referred to as *To-distance*).

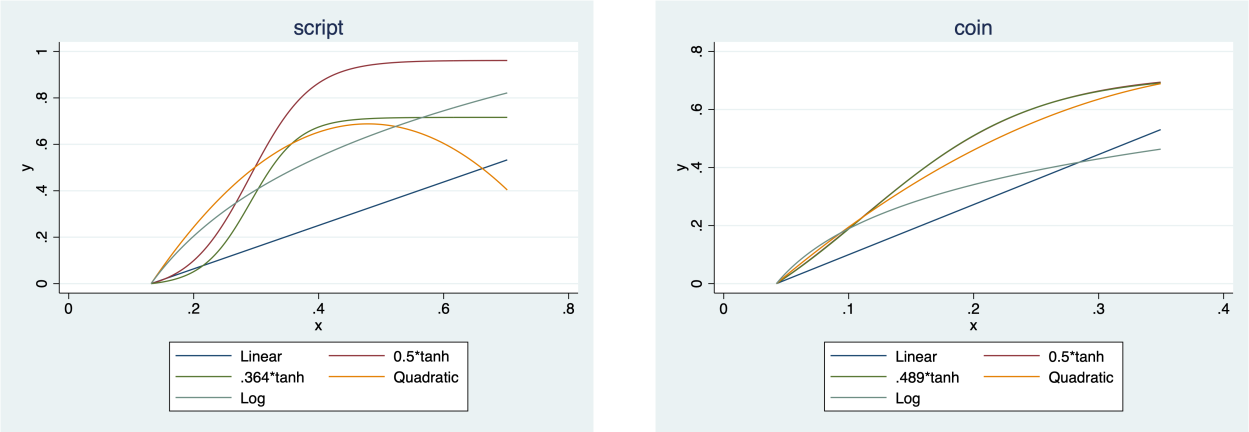
Panel A reports the results using *To-distance*, and Panel B those using *From-distance*. Here we only report specifications with size included as a control variable due to space limits,

Figure 3: Relationship between MA($\mathcal{D}_{i,t-1}$) and adoption in different specifications



(a) Script, without Size

(b) Coinage, without Size



(c) Script, with Size

(d) Coinage, with Size

Notes: Estimation corresponding to Table 1.

but note that similarly as in the case with average cost, the effect of MA($\mathcal{D}_{i,t-1}$) does not change with the inclusion or exclusion of polis size.

We find that the direction of distance matters. In general, *From-distance* is more significant than *To-distance*. When we use *To-distance*, reported in panel A, spatial diffusion is barely significant, except for the linear specification for coinage, with the effect being positive. When we use *From-distance*, reported in panel B, we see significant positive effects of spatial diffusion for both script and coinage in all nonlinear specifications. For script, the ranking of fit according to the AIC value from the smallest to the largest is as follows: the hyperbolic tangent specification with the previously estimated coefficient, the hyperbolic tangent specification with the coefficint set equal to 0.5, the quadratic specification, and the log specification. This ranking coincides with that of the regressions based on average shipping costs, reported in Table 1. The inflection point associated with the hyperbolic tangent specification is at 0.29, and thus close to what we saw before. For coinage, the ranking of our specifications according to the AIC criterion from the smallest to the largest is as follows: the linear, the quadratic, the log, the hyperbolic tangent with the coefficient set equal to 0.5, and the hyperbolic tangent with the previously estimated coefficient, when *To-distance* is used. This is consistent with the fact that the only significant coefficient comes from the linear specification. When *From-distance* is used, that ranking of our specifications becomes: the log, the quadratic, the linear, the hyperbolic tangent with the previously estimated coefficient, and the hyperbolic tangent with 0.5 as its coefficient. We note that the implied inflection point for coinage is 0.03, which is very small suggesting that while the hyperbolic tangent specification is significant, it is most likely capturing the concave part of the function.

In the online appendix, we also plot the estimated relationship between adoption decisions and $\mathrm{MA}(\mathcal{D}_{i,t-1})$ according to the regressions reported in Table 2. They look very like Figure 3.

We interpret the results, when we use asymmetric travel times, as follows. We interpret the *To-distance* measure as less likely to affect deliberate action by a polis — the effect being in a sense somewhat "passive" — whereas the *From-distance* measure more likely affects deliberate action by a polis. The linear positive effect of spatial diffusion with the *To-distance* for coinage more likely captures an exogenous diffusion of knowledge, which is "passive" in the sense that knowledge of the technology just propagates exogenously. The finding of positive and nonlinear effect of spatial diffusion with the *From-distance* and for both script and coinage, suggests that deliberate actions by a polis depend on neighbors' decisions, and the polis' own payoff depends on others' decisions, as in the case of conformity. As as we saw in the estimation results using average costs, a "free rider" effect does not appear to be present, as we do not find a negative effect from having more neighbors that

Table 2: Spatial Diffusion: the Impact of Proximity to Previous Adopters, by Direction

	Linear		0.5*tanh()		0.364/0.489*tanh()		Quadratic		Log	
	(1) script	(2) coin	(3) script	(4) coin	(5) script	(6) coin	(7) script	(8) coin	(9) script	(10) coin
Panel A: TO Distance										
MA($D_{i,t-1}$)	0.546	1.629**	4.080	3.678	4.868	3.766	2.366	1.760	0.260	0.100
	(0.997)	(0.760)	(3.473)	(2.701)	(3.519)	(2.772)	(2.014)	(1.976)	(0.240)	(0.114)
MA($D_{i,t-1}$)^2							-2.231	-0.270		
							(2.682)	(3.579)		
R2	0.202	0.188					0.205	0.188	0.204	0.186
AIC	1349.85	1424.04	1349.56	1428.07	1349.42	1428.07	1347.96	1426.03	1346.77	1427.50
Inflection Pt			0.08	0.16	0.15	0.16				
Panel B: FROM Distance										
MA($D_{i,t-1}$)	1.022	0.511	11.87***	5.623**	15.73***	5.709**	8.634***	3.419	0.634**	0.166
	(0.976)	(1.170)	(4.276)	(2.478)	(5.534)	(2.618)	(2.711)	(2.076)	(0.263)	(0.138)
MA($D_{i,t-1}$)^2							-9.825***	-5.688		
							(3.703)	(3.846)		
R2	0.211	0.187					0.243	0.189	0.222	0.188
AIC	1337.04	1425.69	1287.84	1427.24	1284.63	1427.23	1290.62	1424.75	1320.25	1423.96
Inflection Pt			0.29	0.03	0.29	0.03				
Obs	1151	1499	1151	1499	1151	1499	1151	1499	1151	1499
N(D=1)	410	358	410	358	410	358	410	358	410	358

Notes: Pseudo panel OLS regressions. Columns (1) and (2) are results for regressions linear in MA($D_{i,t-1}$). Columns (3), (4), (5), and (6) are results for regressions with hyperbolic tangent specification. Columns (3) and (4) has the parameter before the tanh($\cdot$) term being 0.5, while columns (5) and (6) has the parameter before the tanh($\cdot$) term being 0.364 (for script) or 0.431 (for coinage). Columns (7) and (8) are results for regressions with quadratic specification. Columns (9) and (10) are results for regressions with MA($D_{i,t-1}$) in natural log. In all specifications, the linear and squared terms of the MA($D_{i,t-1}$) measured in terms of crow-flies distances are controlled for. The distance measures in panel A are distances from other poleis to a polis i, and in panel B are distances from a polis i to other poleis. Size, authority and hub centralities, geographical variables including ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability, as well as proximity to origins (for script regressions) to origins/mines (for coinage regressions) are also controlled for but are not shown. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

have issued coinage.

3.2.2 Heterogeneity

We consider in this section potential heterogeneity effects, that is whether the estimated effects of having more neighbors that have adopted a technology differ across poleis. As we discussed earlier, issuing coinage requires precious metal, and the ability to acquire it differs across poleis due to patterns of trade, varying proximity to mines, polis bargaining power, or even its ability and willingness to exercise brute force. It is reasonable to conjecture that larger, more powerful poleis have greater bargaining power and military strength and therefore greater ease in acquiring precious metal (and other resources). Thus the potential heterogeneity is most likely with respect to polis size.

We approach this question as follows. We divide the observations into two subsamples, poleis with the smallest size, i.e., size being 1, smaller poleis, and poleis with size greater than 1, larger poleis. We rerun the regressions with each of these subsamples.

The results are reported in our online appendix and they do differ across the two subsamples. As we expected, the coefficients of $\text{MA}(\mathcal{D}_{i,t-1})$ are larger and more significant for the larger poleis. Interestingly, the inflection points are larger for the smaller poleis with the hyperbolic tangent specification, likely suggesting that the smaller poleis are more affected by other poleis' adoption decisions and will only adopt when enough neighbors have already done so.

While not reported, we have also tried other groupings of the data, such as smaller poleis defined as those with sizes 1 or 2, or with sizes 1, 2, or 3. With those other groupings, sometimes the regression coefficients are less significant due to smaller number of observations, but the overall pattern remains: larger poleis have coefficients with larger magnitudes.

3.2.3 Role of Time-Invariant Factors on Adoption Dates: Centrality and Distances to Origins

Having established in the previous section the importance of spatial diffusion, which is time-varying, we now focus on the possible role of some key time-invariant explanatory variables. We deem their effects as particularly interesting and compare their relative importance as explanatory variables for the spatial diffusion of adoptions by means of Shapley decompositions along the lines of Huettner and Sunder (2012) and Henderson et al. (2018). The latter is more closely related to our application.

Time-invariant control variables that we deem as particularly interesting include: geographical characteristics including centrality in the travel network, distance to or from potential origins of script diffusion and known mines, and polis size, as stated in section 3.1.1. Trade could affect the demand for both technologies and facilitate their diffusion.

Table 3 reports the estimates for proxies of centrality and the proximity variables defined according to (7). Again, since results excluding and including polis size are very similar, here we only report results with polis size included. But we do report the results excluding size in the online appendix. Panel A shows results for script adoption and panel B shows results for coinage. Columns 1–5 report results with exactly the same specifications as columns 1–10 in Table 1. We also compare them with specifications that do not include the diffusion variables reported in column 6. We carry out robustness checks in the form of survival regressions, in column 7, rather than pseudo-panel regressions, in order to clarify the effects of the time invariant variables. Survival regressions lend themselves conveniently to accommodating censored variables, which is the case for both script and coinage. The spatial diffusion variables are not included in the survival-regressions, as those are in effect cross-sectional specifications. The dependent variable is the survival time, that is time from a defined starting time (in our case a year before the earliest adoption year in the data) until adoption. Thus, a larger value means a later adoption date. To make the estimates of the time-invariant variables readily comparable to those in the pseudo-panel specifications, we convert the signs of the coefficients of all the explanatory variables, so that a positive coefficient means a positive effect of earlier adoption.

The effects of the time-invariant variables are consistent across specifications. Centrality has a strong and positive effect for script adoption. This accords with intuition if such poleis also trade more. Trade gives poleis an incentive to adopt the technology of writing, that facilitated record keeping and ensured greater transactions efficiency. However, when we do not control for the proportion of neighbors that have already adopted, as in columns 6–7, centrality is not significant. This suggests that even if we were interested in the effects of time-invariant factors only, ignoring spatial diffusion could lead to omitted variable bias. Another somewhat surprising to us result is that neither proximity to potential origins nor proximity to Phoenician sites have statistically significant effects. The only exception is proximity to potential *origins* of script diffusion, which is again significant only when the spatial diffusion variables are not controlled for. Polis size has a positive effect on adoption, possibly reflecting the positive effect of state capacity, which is proxied by polis size.

For coinage, centrality has a totally different effect, which is negative and strong. This might be partly explained by properties of the urban hierarchy. While not reported, our data analysis suggests centrality is negatively correlated with size, meaning that more centrally located poleis are on average smaller, while larger poleis are typically located at the periphery of the study area.[33] While not reported here but can be seen from our online appendix, we notice that compared with in the specification not including size, in the specification including size polis centrality has much smaller coefficients. However, the negative effects persist even when size is included. One possible explanation is competition over resources for coinage, namely over precious metals, which is available only from a few mines. Being surrounded by more poleis may imply stronger competition. Another explanation for the effect of centrality on coinage issue could be that less centrally located poleis are more likely to depend on own coinage for trade as they are less likely to benefit from mutual coincidence

---

[33] Larger poleis at the periphery included Syrakousai (Suracuse) and Rhegion, both in current Italy, Rhode in current Spain, but also Ephesus and Rhodos in the Eastern Aegean Sea.

Table 3: Spatial Diffusion: the Impact of Covariates

	Linear	0.5*tanh()	a*tanh()	Quad.	Log	w/o MA(D)	Survival
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Regressions for Script							
EV Centrality	227.8***	208.9***	213.5***	220.1***	217.1***	95.87	182.0
	(76.66)	(75.47)	(76.08)	(74.37)	(74.43)	(64.34)	(195.1)
MA(Phoenician)	0.599	0.418	0.492	0.374	0.466	0.349	-3.933
	(0.819)	(0.844)	(0.843)	(0.839)	(0.824)	(0.868)	(3.864)
MA(Origins)	0.0974	-0.326	-0.323	-0.539	0.0243	3.779**	10.62
	(2.017)	(1.953)	(1.952)	(2.110)	(1.965)	(1.524)	(7.341)
Size	0.0521***	0.0497***	0.0503***	0.0490***	0.0507***	0.0340***	0.131**
	(0.0170)	(0.0160)	(0.0161)	(0.0158)	(0.0166)	(0.0127)	(0.0534)
Delian	0.0354	0.0379	0.0387	0.0381	0.0364	-0.126**	-0.316**
	(0.0583)	(0.0609)	(0.0609)	(0.0587)	(0.0583)	(0.0506)	(0.130)
Koinon	0.240**	0.245**	0.247**	0.238**	0.237**	0.175*	0.314*
	(0.108)	(0.106)	(0.106)	(0.106)	(0.106)	(0.0895)	(0.183)
Obs	1143	1143	1143	1143	1143	2033	890
Panel B: Regressions for Coinage							
EV Centrality	-164.5***	-157.8***	-157.9***	-158.5***	-169.3***	-128.9***	-431.4***
	(57.19)	(59.46)	(59.44)	(58.68)	(58.93)	(30.13)	(106.6)
MA(Sardis)	-2.624	-2.784	-2.785	-2.762	-2.809	-1.676	36.37***
	(2.573)	(2.577)	(2.578)	(2.580)	(2.586)	(1.652)	(10.09)
MA(Mines)	0.748**	0.673*	0.674*	0.683*	0.738*	0.695***	1.965***
	(0.375)	(0.389)	(0.388)	(0.390)	(0.384)	(0.221)	(0.719)
Size	0.139***	0.139***	0.139***	0.139***	0.138***	0.103***	0.306***
	(0.0127)	(0.0126)	(0.0126)	(0.0127)	(0.0127)	(0.00861)	(0.0300)
Delian	0.00146	0.000787	0.000776	0.000943	-0.000129	0.0290	0.150**
	(0.0305)	(0.0300)	(0.0300)	(0.0303)	(0.0302)	(0.0197)	(0.0695)
Koinon	0.0490	0.0502	0.0501	0.0507	0.0498	0.0656***	0.261***
	(0.0325)	(0.0333)	(0.0333)	(0.0333)	(0.0342)	(0.0232)	(0.0740)
Obs	1491	1491	1491	1491	1491	2381	890

Notes: Pseudo panel and survival regressions. Columns (1) - (6) are pseudo panel OLS regressions, and controls for the linear , the hyperbolic tangent with the parameter it being 0.5, the hyperbolic tangent with the parameter it being 0.364/0.489, the linear and squared , the log of, and no term of $\mathrm{MA}(\mathrm{D}_{i,t-1})$, respectively. In Columns (1) - (5), the linear and squared terms of the $\mathrm{MA}(\mathrm{D}_{i,t-1})$ measured in terms of crow-flies distances are also controlled for. Column (7) is survival regressions where the starting dates are assumed to be one year before the earliest observed years in our data for script and coinage. The survival regressions does not include $\mathrm{MA}(\mathrm{D}_{i,t-1})$. We add a negative sign for all coefficients in the survival regressions so that a positive coefficient means a positive effect, to make it comparable to other columns. Polis size, geographical variables are included in all specifications. Panel A has script adoption as the outcome while panel B has coinage as the outcome. The coefficients for centrality, proximity (MA) and size are from specifications without Delian and Koinon. Coefficients for Delian and Koinon comes from the above specification plus the two as additional variables. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

of wants (barter) in trade. Proximity to mines have a strong and positive effect in all specifications, which is expected as metal is necessary for coinage. Size again has positive and significant effects, and the respective regression coefficients for coinage are much larger than for the script regressions. This confirms that state capacity is more important for coinage than for script adoption.

The fact that according to the totality of the historical evidence coinage did originate in Sardis warrants an investigation of how distance from Sardis and distances from known mines compare as explanatory variables in the dynamics of the diffusion of coinage issue. The estimated effect of MA(Sardis)_i is negative, insignificant when size is included but significant when size is not included (see online appendix). This is notable and likely suggests presence of a sphere of influence of Sardis: being nearer it discourages coinage issue, in spite of all other controls. Proximity to mines, on the contrary, has a positive and significant effect. We also note that while not shown, excluding MA(Sardis)_i or MA(Mines)_i has a minimal effect on the coefficients of other variables.

Next we compare the relative importance of the time-invariant variables and the (lagged) spatial diffusion variables by conducting Shapley decomposition exercises for the quadratic specifications reported in Table 1. The results are reported in Panel A of Table 4. For both script and coinage, the local geographical variables play the most important role (when polis size is not included), followed by the lagged spatial diffusion variables, network centrality, period fixed effects, proximity to potential origins of diffusion and mines of precious metals, and proximity to Phoenician colonies and Sardis. Polis size plays a relatively small role for script, but a very important one for coinage. When size is included, it alone accounts for 68% of the overall R^2 for coinage. Panel B and C of Table 4 reports the Shapley decomposition results with the asymmetric (directional) costs, which turn out to be qualitatively very similar to those with symmetric costs.

As mentioned previously, we are also interested in the potential effects of a polis' membership in the Delian League and regional federations, although we do not include them in

Table 4: Spatial Diffusion: Shapley Decomposition

	(1) Script	(2) Coin	(3) Script	(4) Coin
Panel A: Regressions using average cost				
MA(adopters) (Travel cost)	23	18	21	6.7
MA(adopters) (crow-flies cost)	23	17	22	6.2
Local geographical variables	38	30	37	9.5
EV Centrality	8	17	8.1	3.9
Phoenician(Script)/Sardis(Coin)	.58	2.4	.58	.45
Origins(Script)/Mines(Coin)	1.3	5	1.3	1.3
Period FE	6.1	11	5.6	4.3
Size			4.8	68
Panel B: Regressions using To cost				
MA(adopters) (Travel cost)	17	21	16	7.2
MA(adopters) (crow-flies cost)	29	17	27	5.7
Local geographical variables	39	32	38	9.8
Kleinberg Centrality	7.2	11	6.9	3.3
Phoenician(Script)/Sardis(Coin)	.98	1.9	1.1	.36
Origins(Script)/Mines(Coin)	1.2	5.9	1.1	1.6
Period FE	5.8	11	5.4	4.2
Size			4.3	68
Panel C: Regressions using From cost				
MA(adopters) (Travel cost)	35	14	33	5.5
MA(adopters) (crow-flies cost)	19	15	17	5.9
Local geographical variables	35	29	34	9.8
Kleinberg Centrality	3.7	18	3.4	4.7
Phoenician(Script)/Sardis(Coin)	.11	2	.094	.36
Origins(Script)/Mines(Coin)	3.3	12	3.3	2.9
Period FE	4.9	9.5	4.6	3.9
Size			4.2	67

Notes: Shapley decomposition of the total regression R2 for the quadratic specification regressions (corresponding to columns (7) and (8) in Table 1 and Table 2).

the main specification due to endogeneity concerns. The bottom rows of A and B of Table 3 reports the effects of the Delian League and regional federations (Koinon) memberships when they are included as additional explanatory variables to the previous specifications. We note that while not shown due to space limit, controlling for Delian League and Koinon memberships barely changes the effect of MA($\mathcal{D}_{i,t-1}$) and other time-invariant variables . Interestingly, Delian League membership has significant effects only when the diffusion variable MA($\mathcal{D}_{i,t-1}$) is not included (columns 6 and 7). On the contrary, membership in regional federations has persistent positive effects on script adoption across specifications. This could be because polis members of regional federations generated a greater need to communicate with other poleis, and thus stronger incentives to adopt a script, a technology that lowered communication costs.

3.3 Interdependence of Script Adoption and Coinage Issue Decisions

The results reported so far demonstrate that spatial factors have important impact on the adoption of both technologies when they are considered on their own. However, one may wonder how the adoption of one technology may impact the adoption of the other. In our case, since script adoption is generally earlier than coinage issue we consider the impact of former on the latter. [34] There could be a positive effect if script adoption operates as a TFP shock which contribute to polis growth which itself promotes coinage issue. Another possible mechanism, which we owe to a suggestion in Pappa (2019), could be that literacy by having provided for ways to establish trade credit might not have promoted issue of coinage, and indeed might have even obviated its need. Given our discussion in the preceding section, we are also interested in whether spatial factors might have played important roles as omitted variables, when they are not properly controlled for. For example, a more centrally located polis may have had better information (because of many traders going through) and be aware of both technologies prompting it to adopt both earlier. In the other extreme a more remote or isolated polis may have been less advantaged on both accounts and thus more likely to adopt both later. Therefore, a positive correlation between adoptions of the two technologies might be observed, while in fact such correlation might be driven by location in the travel network, if omitted in the estimation, rather than inherent interdependence. We test for such possibilities using script and coinage adoptions.

Working again with the data arranged in a panel structure, we consider a staggered

---

[34] The count of the number of poleis by script adoption and coinage issue status and dates shows that there exist only 22 poleis that adopted a script later than issued coinage. The dates coincide for 9 poleis. See Online Appendix, Supplementary Data.

diff-in-diff specification as follows. We divide the entire length of study into five periods so as to maximize the overlap of adoptions of the two technologies. Details on the count of poleis according to script adoption and issue of coinage and on the distribution of periods are provided in our online appendix. We work with the following regression equation:

$$Coin_{it} = \beta\ \mathbf{1}[t \geq TimeScript_i] + \xi_i + \gamma_t + \varepsilon_{it}, \tag{8}$$

and compare the estimated coefficients β when the variables MA($\text{Coin}_{i,t-1}$) are and are not controlled for.

In view of the recent staggered diff-in-diff literature we investigate this question by employing the methods of Borusyak, Jaravel, and Spiess (2024), BJS for short. Table 5 reports results with both two-way fixed effect (TWFE) model and the imputation method of BJS. One feature of the BJS method is that the "always treated" units would be excluded from the analysis. To make things more comparable, we report the TWFE model results in Panel A, the TWFE model excluding the always treated units in Panel B, and the BJS-based imputation method from the method in Panel C. Since coinage issues happen starting in period 2, MA($\text{Coin}_{i,t-1}$) has positive values only starting in period 3. Given that we proceed in two ways: one, we assign values of zero to all poleis before period 3, see columns 1 and 2; two, we restrict the sample to period 3 and later, see columns 3 and 4. Interestingly, the estimated β does not differ when MA($\text{Coin}_{i,t-1}$) is not included in the TWFE model, but it differs hugely in those two cases with the BJS method. When MA($\text{Coin}_{i,t-1}$) is included, the estimated coefficient for script adoption increases from 0.056 (0.055) to 0.098 (0.093), with the full (later periods) sample.

We also try another specification where we add a "pre-period' to the sample during which there was no script or coinage adoption. With such a "pre-period" we no longer have always treated units. The results are in columns (5) and (6). Again, the TWFE model shows few differences with and without MA($\text{Coin}_{i,t-1}$), but BJS shows an increase from 0.032 to 0.074

when MA($\text{Coin}_{i,t-1}$) is included. We thus conclude that by following BJS with the imputation method that corrects the negative weighting problem for the TWFE specification, omission of the spatial diffusion variable can cause large potential bias even when the individual and time fixed effects are included.

We consider next a cross-sectional analysis where we use the dates of coinage issues as the dependent variable (with censored values filled with 250 BCE), and the dates of script adoption as an independent variable (with censored values filled with 400 BCE). That is:

$$TimeCoin_i = a_0 + a_1 TimeScript_i + \mathcal{X}_i \boldsymbol{\beta} + \varepsilon_i. \tag{9}$$

In such a cross-sectional specification, we cannot include the proportion of previous adopters MA($\text{Coin}_{i,t-1}$), but do try a “distance to origin” instrument.[35] We evaluate the performance of such distance-based instruments with and without time-invariant spatial controls (centrality, in particular).

We report results in Table 7, where columns 1–4 show the OLS results. We report in Panel A results with robust standard errors, and in Panel B those with standard errors clustered at 1 × 1 degree grids. The estimation reported in column 1 includes geographical variables and proximity to mines as controls. As we have previously seen, the adoption of both technologies were affected by spatial diffusion. To account for that in the regression reported in column 2 we control for polis centrality. In both columns 1 and 2, the date of script adoption has a positive effect, although at a slightly smaller significance level when

---

[35] “Distance to origin” instruments have been widely used by other papers. E.g., Becker and Woessmann (2009) and Becker, Cinnirella, and Woessmann (2010) use distance from Wittenberg as an instrument for the shares of Protestants in different German counties and primary education respectively; Ashraf and Galor (2013) use distance from Africa as an instrument for genetic diversity; Franck and Galor (2021); Franck and Galor (2022) use the distance to the origin of steam engine, the first place that commercially adopted steam engines, as the instrument for the number of steam engines in the later periods. But of course, none of those papers use the distance to origin instrument to study the impact of adoption of one technology on the adoption of another technology, which as we show below can be more problematic. Stasavage (2021) also uses the distances from ancient origins of writing (Sumeria, Shang China, and Olmec Mesoamerica) as the instruments for the presence of writing, to estimate its effect on state development. But he noted that “it is possible that my estimates for the effect of writing are also capturing the diffusion of other technologies...”. The possibility that the performance of distance to origin instrument is compromised by spatial factors and the diffusion of other technologies is exactly what we explore in the current paper.

Table 5: Staggered Diff-in-Diff

	Sample: Full		Sample: t>=3		Sample: + Pre	
	(1) coin	(2) coin	(3) coin	(4) coin	(5) coin	(6) coin
Panel A: Two Way Fixed Effect						
script	0.108***	0.102***	0.102***	0.0942**	0.0806***	0.0884***
	(0.0202)	(0.0192)	(0.0391)	(0.0382)	(0.0175)	(0.0163)
Observations	3465	3465	2079	2079	4158	4158
Panel B: TWFE excluding always treated						
script	0.0933***	0.100***	0.0549	0.0934**	0.0806***	0.0884***
	(0.0207)	(0.0197)	(0.0424)	(0.0409)	(0.0175)	(0.0163)
Observations	3010	3010	927	927	4158	4158
Panel C: Borusyak, Jaravel, and Spiess (2024)						
Script	0.0561**	0.0981***	0.0549	0.0925**	0.0324*	0.0740***
	(0.0222)	(0.0231)	(0.0423)	(0.0410)	(0.0189)	(0.0189)
MA(Coin)'s	No	Yes	No	Yes	No	Yes
Obs	3010	3010	927	927	4158	4158

Notes: Staggered difference in difference regressions. Panel A is estimated with two way fixed effect model, panel B is again estimated with two way fixed effect model but has the sample restriction that excludes the always treated units, and panel C is estimated with the imputation method from the method from Borusyak, Jaravel, and Spiess (2024). In columns (1), (3) and (5), no control variable is included. In columns (2), (4) and (6), MA($\text{Coin}_{i,t-1}$) and its squared term, measured both with the travel distance and crow-flies distance are included as a control variable. Since coinage adoption happens starting the second period, MA($\text{Coin}_{i,t-1}$) has positive values only starting period 3. Given that we process in two way: one, give values of zero for all poleis before period 3; two, restrict the sample to period 3 and later (column (3) and (4)). In column (5) and (6), we add a "pre" period to the sample during which there was no script or coinage adoption. But with such a "pre" period we no longer have always treated units. Standard errors clustered at polis level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

clustered standard errors are used. In the regressions reported in columns 3 and 4, we additionally control for polis size, which causes the date of script adoption to have smaller coefficients and be less significant. In both the cases with and without size, we notice that the date of script adoption has larger coefficients when centrality is included, consistent with what we saw with the staggered-diff-in-diff regressions.

As mentioned above, a commonly used identification strategy is to use the distance to some origin as an instrument, and test its validity by "placebo regressions" with distances to other sites. Table 6 reports results with such a procedure for script adoption for the purpose of obtaining a"first-stage test" with such a distance-based IV. The dependent variable is the date of script adoption. It is clear that only the distance to origins of scripts has a

Table 6: First Stage for an Usual Distance to Origin IV

Dependent var: Date of Script Adoption								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MA: Origins of Scripts	-727.6***				-1026.7**			
	(219.1)				(434.6)			
MA: Phoenician sites		132.0				184.8		
		(227.9)				(225.8)		
MA: Mines			-27.01				229.0*	
			(61.23)				(130.4)	
MA: Sardis				701.6				1240.9
				(1837.8)				(2193.8)
Geo controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Centrality	No	No	No	No	Yes	Yes	Yes	Yes
Obs	894	894	894	894	894	894	894	894
R2	0.20	0.15	0.15	0.15	0.20	0.16	0.17	0.16

Notes: OLS regressions of the impact of distances to origins (and other placebo places) on the date of script adoption. It is assumed that all poleis adopted a script by 400 BCE. The distances are measured as from polis i to the those origins. The geo controls include ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability. The centrality includes authority and hub centralities. Here the MA variables are based on the *From-distance*, but results are very similar if we use *To-distance* instead. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

strong positive effect, while the distance to other sites, such as to Phoenician sites or origin of coinage issue (Sardis) and mines of precious metals do not. This seems to satisfy the conditions for a distance-based instrument, as we alluded to earlier. We do notice though that the distances to origins of script becomes less significant when centrality is included.

Columns 5–8 of Table 7 report 2SLS results with the distance to origins of script as an instrument for date of script adoption. We observe the following. First, the distance instrument is stronger when centrality is not included, which is consistent with what we report in Table 6. When centrality is not included, the first stage F-statistic is always greater than 10. Second, spatially clustered standard errors give larger standard errors and smaller first stage $F-$statistics. When neither clustered standard errors are used nor centrality is controlled for, the distance instrument is relatively strong ($F > 45$), but when both clustered standard errors are used and centrality is controlled for the distance instrument is very weak. This hints at the following insight. A cross-sectional regression like equation (9) specifies how adoption of script by a polis affects its issue coinage decision. No spatial factors are explicitly introduced. However, our empirical findings suggest that ignoring spatial factors can still lead to misleading inference. Ignoring spatial factors makes the distance instrument look strong while in fact it is weak.

Table 7: OLS and 2SLS Results with a Distance to Origin IV

Dependent var: Date of Coinage								
	OLS				2SLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Script Date	0.107	0.153	0.040	0.072	-0.512	0.074	-0.340	-0.005
	(0.042)	(0.041)	(0.037)	(0.036)	(0.190)	(0.196)	(0.144)	(0.169)
	[0.065]	[0.055]	[0.045]	[0.040]	[0.271]	[0.154]	[0.185]	[0.145]
Size			-43.608	-41.143			-46.518	-41.912
			(2.459)	(2.540)			(3.056)	(3.111)
			[2.816]	[3.057]			[3.904]	[3.595]
Geo controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MA(Mines)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Centrality	No	Yes	No	Yes	No	Yes	No	Yes
F-stat.(robust se)					33.69	20.25	31.40	18.33
F-stat.(clustered se)					9.52	5.19	9.39	4.88
Obs	894	894	894	894	894	894	894	894

Notes: OLS and 2SLS regressions of the impact of date of script adoption on date of coinage. It is assumed that all poleis adopted a script by 400 BCE and a coinage by 250 BCE. Columns (1) - (4) are OLS regressions while columns (5) - (8) are 2SLS regressions with proximity to script origins as the instrument. In all specifications, proximity to mines and geographical variables including ruggedness, malaria index, temperature, precipitation, elevation, and crops (barley, millet, summer wheat and winter wheat) suitability are included. In columns (2), (4), (6), and (8), authority and hub centralities are included. The first stage Kleibergen-Paap F tests are shown for 2SLS regressions. Robust standard error in parentheses and standard error clustered at 1 by 1 degree grids in brackets. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

We conclude that ignoring spatial factors can complicate inference in the estimation of the impact of the adoption of one technology on that of the other. Even with a staggered diff-in-diff setting and individual fixed effects, failure to account for the spatial diffusion variables can cause omitted variable bias. In the staggered diff-in-diff or cross-sectional OLS setting, ignoring the spatial variables causes the coefficient of script adoption to be much smaller. In a cross-sectional setting with a distance to origin type of instrument, ignoring spatial factors, that is by not including overall location measures such as polis network centrality and not using spatially clustered standard errors, can make the distance instrument looks strong and valid while it is actually weak.

4 Conclusions

To conclude, we underscore that we aim at contributing to a better understanding of the diffusion of two revolutionary technologies in ancient times. Our study relies critically on unusual and hitherto quantitatively unexplored data, some of which we ourselves coded from the scholarly literature, on the diffusion of the epichoric scripts and coinage. The epichoric scripts were the local versions of the Hellenic alphabet that served as vehicles for its diffusion in the preclassical and classical Hellenic era. It is accepted that the Hellenic alphabet originated in the Phoenician script, that is alphabet. The paper aims at elucidating the process by which its adoption diffused over time in the Hellenic poleis. Regarding coinage, it is known that it originated in Sardis, an ancient non-Hellenic city. What is not known is how issuance of coinage diffused in the ancient Hellenic poleis. Coinage is of enormous significance as a form of money, an innovative concept, that satisfied its key roles as a store of value, medium of exchange and unit of account.

The convenience of alphabetic writing facilitated mass literacy, written communication and recording of knowledge. Therefore its impact on the evolution of human civilization and all the extraordinary human developments that followed are difficult to exaggerate [Cross (1989)]. Coinage, too, was a revolutionary invention that served as a vehicle for storage and transmission of information about means of payment and state capacity across space and time. Therefore it contributed not only to the economic but also the political life of early city states and helped accelerate their economic integration [Pavlek (2021)].

Our study is made possible by our merging of our unique data with geographic information about the system of Hellenic poleis. We explore and evaluate several potential mechanisms of spatial diffusion and the role of spatial spillovers. We also compare the overall importance of spatial spillovers with other geographical and economic forces. Finally, we investigate the possibility that spatial factors might be influential omitted variables in the quantitative relationship between the adoption of one technology and that of the other.

References

Allen, Treb and Costas Arkolakis (2014). "Trade and the Topography of the Spatial Economy". In: *The Quarterly Journal of Economics* 129(3), pp. 1085–1140.

Ashraf, Quamrul and Oded Galor (2011). "Dynamics and stagnation in the Malthusian epoch". In: *American Economic Review* 101(5), pp. 2003–2041.

Ashraf, Quamrul and Oded Galor (2013). "The "Out of Africa" hypothesis, human genetic diversity, and comparative economic development". In: *American Economic Review* 103(1), pp. 1–46.

Bass, Frank M (1969). "A new product growth for model consumer durables". In: *Management science* 15(5), pp. 215–227.

Becker, Sascha O, Francesco Cinnirella, and Ludger Woessmann (2010). "The trade-off between fertility and education: evidence from before the demographic transition". In: *Journal of Economic Growth* 15, pp. 177–204.

Becker, Sascha O and Ludger Woessmann (2009). "Was Weber wrong? A human capital theory of Protestant economic history". In: *The quarterly journal of economics* 124(2), pp. 531–596.

Bloch, Francis, Matthew O. Jackson, and Pietro Tebaldi (2019). *Centrality Measures in Networks*. URL: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2749124`.

Borusyak, Kirill and Peter Hull (2023). "Non-Random Exposure to Exogenous Shocks: Theory and Applications". In: *Econometrica* 91(6), pp. 2155–2185.

Borusyak, Kirill, Xavier Jaravel, and Jann Spiess (2024). "Revisiting event-study designs: robust and efficient estimation". In: *Review of Economic Studies*, rdae007.

Bourogiannis, Giorgos (2021). "Phoenician writing in Greece: content, chronology, distribution and the contribution of Cyprus". In: *LRBT. Dall'archeologia all'epigrafia/De l'archéologie à l'épigraphie: Studi in onore di Maria Giulia Amadasi Guzzo/Études en hommage à Maria Giulia Amadasi Guzzo*. Brepols Publishers, pp. 99–127.

Bresson, Alain (2005). *The Origin of Lydian and Greek Coinage: Cost and Quantity.* 3rd International Conference of Ancient History, Fudan University, Shanghai, August 17–21.

Bresson, Alain (2016). *The Making of the Ancient Greek Economy: Institutions, Markets, and Growth in the City-States.* Tech. rep. Princeton University Press.

Brock, William A and Steven N Durlauf (2001). "Discrete choice with social interactions". In: *The Review of Economic Studies* 68(2), pp. 235–260.

Cahill, Nicholas et al. (2020). "Depletion Gilding of Lydian electrum coins and the sources of Lydian gold". In: *White Gold.* Ed. by Peter Van Alfen and Uta Wartenberg. American Numismatic Society: New York, pp. 291–336.

Chen, Yuxian, Yannis M. Ioannides, and Ferdinand Rauch (2022). *Asymmetric Trading Costs and Ancient Greek Cities.* Presented at the Urban Economics Association. CEPR DP 17204. Tufts University Working paper. URL: `https://sites.tufts.edu/yioannides/files/2022/11/Chen_Ioannides_Rauch_Asymmetric_11.20.22.pdf`.

Comin, Diego A, Mikhail Dmitriev, and Esteban Rossi-Hansberg (2013). "The Spatial Diffusion of Technology". In: *NBER Working Paper*(w18534).

Cross, Frank Moore (1989). "The Invention and Development of the Alphabet". In: *The Origin of Writing.* Ed. by Wayne M. Senner. University of Nebraska Press: Lincoln.

D'Angour, Armand J (1999). "Archinus, Eucleides and the Reform of the Athenian Alphabet 1". In: *Bulletin of the Institute of Classical Studies* 43(1), pp. 109–130. DOI: `10.1111/j.2041-5370.1999.tb00481.x`.

Database, Poinikastas (2004). *Poinikastas Database.* URL: `http://poinikastas.csad.ox.ac.uk/`.

Dittmar, Jeremiah E (2011). "Information technology and economic change: the impact of the printing press". In: *The Quarterly Journal of Economics* 126(3), pp. 1133–1172.

Economou, Emmanouil Marios L, Nicholas C Kyriazis, and Theodore Metaxas (2015). "The institutional and economic foundations of regional proto-federations". In: *Economics of Governance* 16, pp. 251–271.

Franck, Raphaël and Oded Galor (2021). "Flowers of evil? Industrialization and long run development". In: *Journal of Monetary Economics* 117, pp. 108–128.

Franck, Raphaël and Oded Galor (2022). "Technology-skill complementarity in early phases of industrialisation". In: *The Economic Journal* 132(642), pp. 618–643.

Hansen, Mogens Herman and Thomas Heine Nielsen (2004). *An inventory of archaic and classical poleis*. Oxford University Press: Oxford.

Henderson, J Vernon et al. (2018). "The global distribution of economic activity: nature, history, and the role of trade". In: *The Quarterly Journal of Economics* 133(1), pp. 357–406.

Herodotus (Circa 430 BCE). *Histories*. URL: `http://www.perseus.tufts.edu/hopper/text?doc=Hdt.+5.58&fromdoc=Perseus%3Atext%3A1999.01.0126`.

Hodos, Tamar (2020). *The archaeology of the Mediterranean Iron Age: a globalising world c. 1100–600 BCE*. Cambridge University Press.

Huettner, Frank and Marco Sunder (2012). "Axiomatic arguments for decomposing goodness of fit according to Shapley and Owen values". In: *Electronic Journal of Statistics* 6, pp. 1239–1250.

Ioannides, Yannis M. (2013). *From Neighborhoods to Nations: The Economics of Social Interactions*. Princeton University Press.

Ioannides, Yannis M. (2019). *Cities Ancient, Medieval, Modern: An Economics Perspective.* Inaugural Lecture. In Greek. June 5, 2018. Academy of Athens.

Jeffery, Lilian H and Anna Morpurgo-Davies (1971). "An Archaic Greek Inscription from Crete". In: *The British Museum Quarterly* 36(1/2), pp. 24–29.

Jeffery, Lilian Hamilton (1961). *The Local Scripts of Ancient Greece. A Study of the Origin of the Greek Alphabet and Its Development from the Eighth to the Fifth Centuries B.C.* Oxford University Press.

Jeffery, Lilian Hamilton and Alan Johnston (1990). *The local scripts of archaic Greece: a study of the origin of the Greek alphabet and its development from the eighth to the fifth centuries BC*. Second. Oxford University Press.

Johnston, Alan (1998). "Epichoric alphabets: The rise of the Polis or a slip of the pen?" In: *Die Geschichte der hellenischen Sprache und Schrift vom*. Ed. by N. Dimoudis and A. Kyriatsoulis. Vol. 2, pp. 419–431.

Kallet, Lisa and John H. Kroll (2020). *The Athenian Empire: using coins as sources*. Cambridge University Press.

Kiszewski, Anthony et al. (2004). "A global index representing the stability of malaria transmission". In: *American Journal of tropical medicine and hygiene* 70(5), pp. 486–498.

Kleinberg, Jon M (1999). "Authoritative sources in a hyperlinked environment". In: *Journal of the ACM (JACM)* 46(5), pp. 604–632.

Konno, Tomohiko and Yannis M. Ioannides (2019). "The exact solution of spatial logit response games". In: *Mathematical Social Sciences* 97, pp. 1–10.

Kroll, John H. (2010). *The Coins of Sardis*. URL: `https://sardisexpedition.org/en/essays/latw-kroll-coins-of-sardis`.

Kroll, John H. (2013). "Hacksilber". In: *The Encyclopedia of Ancient History*. Wiley.

MacKil, Emily (2013). "The Greek Koinon". In: *The Oxford Handbook of the State in the Ancient Near East and Mediterranean*. Ed. by Peter Fibiger Bang and Walter Scheidel. Oxford Handbooks Online: Oxford.

Masschaele, James (1993). "Transport Costs in Medieval England". In: *Economic History Review*, pp. 266–279.

Melitz, Jacques (2017). "A model of the beginnings of coinage in antiquity". In: *European Review of Economic History* 21(1), pp. 83–103.

Nunn, Nathan and Diego Puga (2012). "Ruggedness: The blessing of bad geography in Africa". In: *Review of Economics and Statistics* 94(1), pp. 20–36.

Özak, Ömer (2010). *The voyage of homo-economicus: Some economic measures of distance.* URL: `https://github.com/human-mobility-index/human-mobility-index.github.io`.

Özak, Ömer (2018). "Distance to the pre-industrial technological frontier and economic development". In: *Journal of Economic Growth* 23(2), pp. 175–221.

Pappa, Eleftheria (2019). "The poster boys of antiquity's "capitalism" shunning money? The spread of the alphabet in the Mediterranean as a function of a credit-based, maritime trade". In: *Revista do Museu de Arqueologia e Etnologia*(33), pp. 91–138.

Pavlek, Barbara (2021). "The cultural evolution of coinage as an informational system". PhD thesis. Friedrich Schiller University Jena, Faculty of Philosophy. URL: `https://www.db-thueringen.de/receive/dbt_mods_00048173?r=275809&lang=en`.

Quinn, Josephine C. (2024). *How the World Made the West.* Penguin Random House.

Robinson, Andrew (2009). *Writing and script: a very short introduction.* Vol. 208. Oxford University Press, USA.

Schaps, David M. (2004). *The invention of coinage and the monetization of ancient Greece.* University of Michigan Press.

Schaps, David M. (2007). "The Invention of Coinage in Lydia, in India, and in China". In: *Bulletin du Cercle d' Etudes Numismatiques* 44, pp. 281–300, 313–322.

Seaford, Richard (2004). *Money and the early Greek mind: Homer, philosophy, tragedy.* Cambridge University Press.

Stasavage, David (2021). "Biogeography, Writing, and the Origins of the State". In: *The Handbook of Historical Economics.* Elsevier, pp. 881–902.

Van Alfen, Peter and Uta Wartenberg (2020). *White Gold: Studies in Early Electrum Coinage.* American Numismatic Society.

Vaxevanopoulos, Markos et al. (2022). "New findings of ancient Greek silver sources". In: *Journal of Archaeological Science* 137, p. 105474.

Whitewright, Julian (2011). “The potential performance of ancient Mediterranean sailing rigs”. In: *International journal of nautical archaeology* 40(1), pp. 2–17.

Woodard, Roger D. (1997). *Greek Writing from Knossos to Homer: a linguistic interpretation of the origin of the Greek alphabet and the continuity of ancient Greek literacy.* Oxford University Press.

Young, H. Peyton (2009). “Innovation diffusion in heterogeneous populations: Contagion, social influence, and social learning”. In: *American economic review* 99(5), pp. 1899–1924.

Zabel, Florian, Birgitta Putzenlechner, and Wolfram Mauser (2014). “Global agricultural land resources–a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions”. In: *PloS one* 9(9), e107522.