The Diffusion of alphabetic Writing and Coinage in the Ancient Greek Cities [1]

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Abstract. Little is known about the exact diffusion of alphabetic writing and minting of coins in spite of their being among the most significant innovations in history. This paper explores the dynamics of their spatial diffusion in the ancient Greek cities. Using information on dates of adoption by each city, 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 mainly in the adoption of alphabetic writing. We find evidence supporting conformity in the adoption of alphabetic writing and deliberate interaction among cities in the adoption of both technologies. We find that preceding adoptions are more important than such time-invariant spatial factors as a city's location in the network and its proximity to potential origins of both innovations, and for coinage to mines of precious metals. We find that ignoring spatial factors can cause biases in estimating the impact of the adoption of alphabetic writing on the minting of coins.

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1 Introduction

This paper studies the diffusion of two foundational technological and ultimately institutional innovations in the ancient Mediterranean world: alphabetic writing and coinage. Alphabetic writing reduced the fixed costs of literacy and record keeping relative to earlier forms of writing, while coinage standardized value and facilitated impersonal exchange. While each has been studied extensively in isolation, though only outside economics, their diffusion occurred broadly within the same historical environment. Thus, we find it informative to examine both in a single paper, comparing how their spatial patterns overlap and differ. In both cases, adoption required collective acceptance and institutional support, as evidenced by the fact that the speed of adoption was much slower than intercity travel times. The central premise of this paper is that cities' adoption decisions depended not only on local productivity, micro-geographic conditions and intercity travel times, but also on the adoption status of economically interconnected and institutionally and culturally similar polities, the ancient Greek city-states.

We believe it is important to analyze the diffusion of alphabetic writing and minting of coins in a single paper. Those two technologies were critical innovations in the history of technology that developed and diffused in roughly the same institutional setting and historical era. It is natural to ask, were the dynamics of their spatial diffusion different?

Adoption of different versions of the Greek alphabet in the form of mutually intelligible scripts confers benefits to all parties within and across cities but possibly not uniformly, much like a non-rival public good though with little resource cost. In contrast, the minting of coins requires knowledge of the respective technology and sources of precious metals and thus can be affected by competition. However, a city did not have to mint its own coins. It could trade using coinage of other cities, which it could acquire through trade or plunder.

One may also wonder, what was the role of their potential interdependence? For example, the earliest coins did not include lettering, which would suggest independence. However, Pappa (2019) suggests that literacy, by having provided ways to establish trade credit by means of written agreements, might have actually obviated the need for coinage, at least in so far as its significance for trade was concerned.[2] The diffusion of alphabetic writing preceded that of coinage on average one to two centuries. This allows us to use those two technologies as a setting to study the effect of adopting the former technology on that of the latter.

Together, the adoption of those innovations helped solidify the concept of a polis, city. As communication technologies both were crucial for the functioning of the cities as economic and social entities and not just dense population settlements. Studying the diffusion of those innovations contributes to a better understanding of the ancient urbanization process — that it was qualitatively much more than emergence of dense settlements — to which the present study also seeks to contribute.[3]

The paper's contribution is to shift attention from origins, the purview of humanities, linguistics and ancient history, to diffusion, to which institutional factors and human action contribute. Rather than asking why writing or coinage emerged in particular locations, we ask how and why they spread across a system of cities that were geographically dispersed

[2]Barjamovic et al. (2019) show that trade between Upper Mesopotamia and Anatolia was possible through direct connections between traders that shared kin connections, language and script, without widespread adoption of their writing system, the cuneiform script.

[3]"Around 600 BCE, the Greeks were in a phase of transition towards a market economy" Bresson (2005); Schaps (2004).

but culturally and economically linked. This perspective allows us to reconcile the lessons learned from what might have been considered localized historical phenomena with broader regularities in technology adoption patterns.

We propose and estimate a framework in which adoption generates positive externalities. Trade links, migration, and political interaction transmit exposure and create strategic complementarities across cities. These mechanisms generate threshold effects, path dependence, and clustering, consistent with the historical record. The paper makes three main contributions. First, it documents parallel diffusion patterns for writing and coinage across the ancient Mediterranean. Second, it develops a unified empirical framework in which exposure through networks of interaction governs adoption dynamics. Third, it highlights how institutional complementarities can amplify diffusion even when the underlying technologies are distinct.

1.1 Literature on Technology Diffusion and Adoption

There is a long-standing literature on the historical adoption of an extensive set of technologies and their persistent effects. Comin, Easterly, and Gong (2010) assemble and work with data on technology adoption in 1000 BCE, 0 CE, and 1500 CE and show that technology adoption in the past has a persistent effect on current income level and technology adoption. They also estimate significant effects of preceding technology adoptions on subsequent ones, arguably because the cost of adopting a new technology declines with the stock of existing technologies. They focus more on the dynamics of technology adoption, treating it as a matter of individual choice and ignoring externalities — the very focus of the present paper. Although we study just two technologies, they are two profoundly revolutionary ones and representative of rival and non-rival types.

Comin and Hobijn (2004) and Comin and Hobijn (2010) explore technology adoption in a relatively more modern setting (over the last two centuries), but also focus on the role of a nation's own characteristics on adoption. Comin and Hobijn (2004) take a more empirical approach in investigating the effects of human capital stock, institutions, openness to trade, and adoption of predecessor technologies; Comin and Hobijn (2010) take a more structural approach and estimate adoption lags. In contrast, the present paper evaluates the effects of adoption externalities and assesses the importance of cities' own characteristics relative to those of adoption externalities (interpreted as spatial spillovers). Comin, Dmitriev, and Rossi-Hansberg (2013) work with the same dataset as Comin and Hobijn (2004) and Comin and Hobijn (2010), but they also examine the spatial diffusion of technologies over time. They find that proximity to adoption leaders has a positive effect on subsequent adoptions. Our conceptualization is more closely related to Comin, Dmitriev, and Rossi-Hansberg (2013), but our analysis differs from theirs in that we focus on a much earlier historical period, 700–300 BCE, rather than since 1800 CE, and further investigate potential nonlinearities in the effect of proximity to prior adopters.

Another strand of literature studies the effect of technology on urban development, using spatial diffusion from specific origins to explain the pattern of technology adoptions. Among them most noteworthy and conceptually related to our paper is Dittmar (2011), who evaluates the effect of adoption of the movable-type printing press during 1450–1500 CE on the growth and intellectual development of European cities. He uses the distance from Mainz (that technology's origin) as an instrument for the adoption of that technology and finds that the geographical diffusion was an important determinant of the adoption pattern. Stasavage (2021) argues that ancient adoption of writing systems contributes to state development, using distances to three potential origins (Ancient Sumeria, Ancient China and Mesoamarica) as the instrument for presence of writing. Stasavage does recognize that all alphabetic writing originates in the Phoenician script, via the invention of the Greek alphabet. Similar applications include Franck and Galor (2021) and Franck and Galor (2022), both of which use the distance to the origin of the steam engine as the instrument for the number of steam engines installed.

A different strand of the literature studies the dynamics of the spread of social innovations by modeling them as coordination games played in social networks. Specifically, Young (2011) shows that the speed with which a social innovation is adopted depends principally on the topology of the network, the payoff of the innovation relative to the status quo, and the amount of noise in the best response process. Most recently, Reich (2023) develops a model of innovation diffusion which assumes that adoption of an innovation is considered jointly by a number of neighbors in a social network.[4]

This paper relates to the literature on technology and institutional diffusion, which emphasizes learning, imitation, and network effects. Early models stress geographic proximity, while more recent work incorporates strategic interaction and threshold adoption. Our analysis builds on this literature by applying diffusion concepts to institutional change in a premodern setting. The paper complements this work by focusing on the spread of these institutions across cities rather than their initial emergence. Finally, the paper connects to recent work that applies formal economic reasoning to ancient history. By combining historical evidence with diffusion theory, we provide a parsimonious explanation for observed adoption patterns without attributing them solely to exogenous technological shocks.

2 Historical Background

2.1 Alphabetic Writing

Alphabetic writing was an *invention* of a new system of writing whereby symbols represent individual sounds and in the case of the Greek alphabet two symbols together represent syllables. Its adaptation and widespread use amounted to an *innovation.* While an earlier form of writing of the Greek language, known as Linear B, existed several centuries prior to the emergence of alphabetic writing, it vanished in the Bronze Age Collapse, 1190–1150

[4]Reich (2023) also assumes that once an adoption is made individuals cannot switch back, a feature that is particularly interesting in our setting. That second feature may be modified to yield a best-response updating process, as in Young (2011). Kreindler and Young (2014) examine diffusion in social network settings.

BCE. The gap between the two writing systems, as evidenced by the lack of epigraphic evidence, is known as *Greek Dark Ages*. It has puzzled scholars, especially since such a gap is not observed in Cyprus.

Alphabetic writing's origin in the *Northwest Semitic* (Phoenician) script is well accepted; it is even betrayed by its being referred to in the classical Hellenic world as *Phoenician Letters* [$\Phi o\iota\nu\iota\kappa\acute{\eta}\iota\alpha \quad \Gamma\rho\acute{\alpha}\mu\mu\alpha\tau\alpha$]. According to Herodotus, 5.58, Phoenicians who allegedly came to Greece with Cadmus (the mythological founder of the ancient Greek city of Thebes) brought with them the alphabet.

Although Herodotus' claim is widely cited, two arguments prompt a deeper assessment. One, the claim mixes history with mythology; and two, archaeological evidence referring to the Greek letters as Phoenician *predates* Herodotus; see Lilian H. Jeffery and Morpurgo-Davies (1971). In fact, modern scholarship argues that it was probably Greek speaking users of the *Northwest Semitic Script* who developed what came to be known as the Greek alphabet. They did so by 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); Johnston (2022)]. Although most scholars agree that this probably happened once, *where*, *when* and *how* that occurred continues to be vigorously debated; in particular, see Steele (2021).

If that was indeed the case, a followup question is what happened next. That is, did the invention, the concept of alphabetic writing, travel *directly* to various locations, and was it adapted locally? Or was it through a sequential decentralised process that alphabetic writing was transmitted from one to another city? In either case, existence of many variants is compatible both with direct transmission from the original invention and local adaptation as well as sequential diffusion throughout the system of the ancient Greek cities.

The different scripts that are attested in the archeaological record share similarities but also exhibit differences. To give a sense of the debate, from among the most recent contributions to this literature, Astoreca (2021), on the one hand, emphasizes the differences among the scripts on linguistic grounds. Astoreca hypothesizes a proto-alphabet, an *Uralphabet*, that served as a direct ancestor of the local alphabets. Steele (2021), on the other hand, treats the local alphabets as outcomes of local experimentation over letter shapes and writing conventions that "are the result of local processes of standardisation," which are arguably "related to the development of local social and political structures," an inherently decentralized process. Writing required coordination and shared conventions, making its value increasing in the number of users. These features render diffusion a collective process rather than a series of independent local decisions.

2.2 Coinage

It is widely established that minting of coins, the creation of standardized pieces of metal that were stamped with the authority of the state, was *invented*, at least in the Eastern Mediterranean (and most likely globally [Schaps (2007)], too) in Sardis, an ancient non-Hellenic city state in Lydia (now in Turkey). It, too, led to an *innovation* in the form of a standardized medium of exchange whose stamp conveyed trust, that diffused in the ancient Hellenic world largely later than the alphabet.

Early coin issuance required control over metal supplies and mechanisms to enforce precious metal content, tying coinage closely to state capacity. Coinage facilitated taxation, military and public project finance and long-distance trade, reinforcing both market integration and political power. These features generated complementarities across adopters, as the usefulness of coinage increased with its acceptance by trading partners.

However strange it might appear to modern readers, the classics literature takes pains to establish that it was indeed a revolutionary notion that coinage represented *value*. Prior to coinage, quantities of precious metals (coin hoards or bullion) had been used in effect as commodity money. However, the accumulated hoards of precious metals were not originally perceived as money as such.[5] As Melitz (2017) argues, a certification process together with

[5] See Schaps (2004) and Seaford (2004). The reasons coins were issued in the first place is also debated by

trust were necessary to make coins able to travel and be negotiable as money, with their market value exceeding the value of its metal content.

3 Data

3.1 The Cities Data

We rely extensively on the Polis Project data from http://polis.stanford.edu/, whose digitized information originates in the *Inventory of Archaic and Classical Cities* [Hansen and Nielsen (2004)], a detailed compilation of the entirety of the archaeological and historical data for 1037 archaic and classical Hellenic poleis by the Copenhagen Polis Centre. Some of the data were digitized by Josiah Ober and his team of Stanford and Oxford scholars, but we too digitized some additional details from the same source.[6] Figure 1a shows a map of cities used in this paper. While cities did trade with non-Hellenic city-states and sites — including very distant ones, as documented by Quinn (2024) — the center of the action for the diffusion of the Greek alphabet and minting of coins were ancient Greek cities, and therefore our emphasis on them does not bias our estimations.[7]

Important variables that we use from these data include: size, fame, and geographical coordinates. Also interesting are such variables as colonies founded by poleis and their colonizers, participation in the Delian League (a monetary union under the hegemony of Athens), and *Koinon* (participation in a regional federation of which there were many). Although the former is "less endogenous" than the latter, endogeneity concerns make us cautious in using them.

Size is a complex matter, as Hansen and Nielsen discuss [*ibid.* 70–73], and is thought

the literature, but is not discussed here. In this connection, see Bresson (2005). For the advantages of coinage over bullion see Kroll (2013). For an ingenious use of data on coin hoards, see Boehm and Chaney (2024).

[6] We are grateful to Peter Van Alfen for some key clarifications on the coinage data.

[7] Also, even when we consider Phoenician colonies and sites in section 4, we show that distances to Phoenician colonies have little impact on script adoption conditional on distances to all sites of potential origins; see also Quinn (2024).

of as a proxy for city size and influence; it is defined categorically in terms of ranges of city territory: $[0-25), [25-100), [100-200), [200-500), \geq 500$ km^2 [*ibid.* p. 7]. It is available for only 635 of 1037 cities; *ibid.* p. 71. A second variable in the data that is intuitively close to size is fame, and is measured by the number of eights of columns of text devoted to the respective city in Hansen and Nielsen (2004). It proxies for the prominence of a given city as seen through the archaeological record. Because fame is available for all cities, we use it to predict size for cities with missing size data.[8] Of the 1037 cities in *ibid.*, 143 cities lack location information. Since our analyses rely heavily on location information, our quantitative analysis will be restricted to (at most) the 894 cities with known locations. We merge these data with micro-geographic information from other sources, which we use extensively in our estimations reported in section 4 below.

3.2 Greek Alphabets and Coinage Data

Prior to discussing our data on alphabetic writing and coinage in detail, we note that we are unaware of any previous use of the data in studying their diffusion in any systematic fashion and their treatment as technological innovations and thus as economic phenomena.

The data for the adoption of alphabetic writing come from the *Poinikastas* Database, a digitization of the entire archive underlying Lilian H. Jeffery and Johnston (1990).[9] Our data set includes adoption times by cities for 174 epichoric scripts. Since some scripts are associated with the regions where cities lie, 622 cities may be matched with at least one script. Among them, 128 cities are directly matched with a script, that is, not via their regions. The dates of attested adoption of alphabetic writing, thus defined, range from 725 BCE to 416 BCE. Figure 1b shows the location of cities with scripts: red dots indicate cities

[8] Fame, a continuous-valued variable, and size are (not surprisingly) quite highly correlated. Fame may be thought of as reflecting the total impact of the entire urban system on a polis. Therefore, fame is a different outcome from size, as it reflects a polis' impact through a combination of the historical and archaeological records and thus likely to reflect a multitude of other factors that pertain to scholarship traditions and the like. Therefore, its endogeneity reflects forces in addition to those of size and we therefore are not using the variable fame in this investigation.

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

directly matched with a script, green dots cities matched with a regional script. To the best of our knowledge, the *Poinikastas* data base has not been used before by an economics study, and indeed by any quantitative study.

Data on coinage are taken from two sources. One is available in the original database of the Stanford Polis Project and records time of issue by century; the second was coded manually by ourselves and uses the more detailed information available in Hansen and Nielsen, *op. cit.,* either according to attested approximate year or approximation by interval midpoints (an imprecise measure). 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 coinage. Figure 1c and Figure 1d show the locations of cities that issued coinage for which precise and imprecise dates are available, respectively. Gold and electrum coinage are much rarer. In our data 21 cities issued gold coins and 9 cities issued electrum coins.[10]

We do not differentiate in this paper between the types of coinage and consider only the *earliest* date of coinage issue if a city issued multiple coin types in its history. A histogram showing the number of adopters by dates in years is given by Figure 2.[11] For both alphabetic writing and coinage, it takes centuries until all cities adopt. This suggests that the adoption processes involve more than passive diffusion of knowledge, as knowledge in principle travels from city to city at the speeds of travel, which takes no more than two months for two of the most distant cities in our data; Scheidel and Meeks (2012). The long process of adoption is reasonable as inventions must be comprehended first and their value assessed by the respective institutions before being adopted.

The adoption processes of both technologies are censored in our data. The one for alphabetic writing is censored at 403-402 BCE, when Athens legislated the adoption of the Ionic script, which became increasingly standard thereafter in much of ancient Greece.

[10]The numismatics literature has concluded that electrum coins were the first ones to be issued with Sardis being first; see Hodos (2020), Kallet and Kroll (2020), Ch. 3, and Van Alfen and Wartenberg (2020).

[11]While not reported here, the aggregate adoption curves for both alphabetic writing and coinage are roughly sigmoid.

Ultimately, all cities adopted a script [D'Angour (1999); Johnston (2022)].[12] The coinage process is censored at around 250 BCE. Especially after the conquests by Alexander the Great in the late fourth century BCE and emergence of many new city-states, coinage became ubiquitous. Still, not all cities are attested to have ever issued coinage. The fact that trade was known to be widespread suggests that it was possible for cities to trade without issuing their own coinage. Thus, when analysing the role of the time-invariant variables in section 4.4, we use survival analysis, which accounts for both the extensive and intensive margin, as a robustness check for both technologies. The results confirm that our main specification is robust.

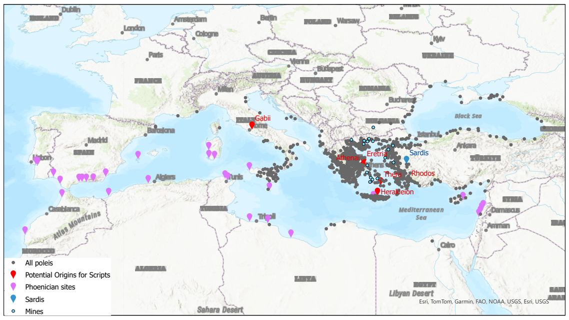
3.2.1 Alphabetic Writing and Coinage As Inventions

Some of the technology diffusion literature distinguishes between the place and time of *invention* as distinct from those of its *adoption* possibly elsewhere, when this is made possible by the data [c.f. Comin and Hobijn (2010)]. In our case, we have some information about the former, which we call the *origin*, and consider the effect of a city's being close to it. But it is the latter that is the focus of our investigation.

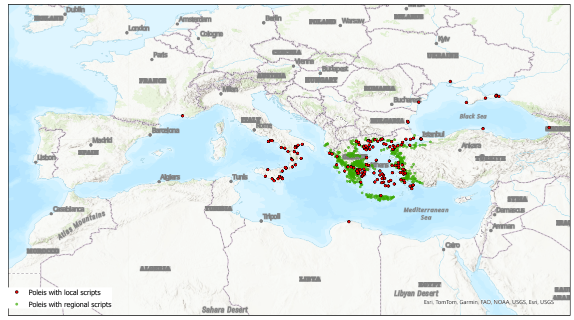
With our data, for both alphabetic writing and minting of coins we do know from the historical and historical records the times and places of adoption as *attested* instances of alphabetic inscriptions and minting of coins. For coinage, the place and time of its invention are attested to be Sardis in 625–600 BCE. That is not the case for alphabetic writing. While we know a few places as the candidates of potential origin, we cannot argue with certainty in which one of them its invention happened. In addition, although the Phoenician script predates the Greek alphabet, we do not know whether the Phoenician script was first adapted into a local, known as *epichoric* script, which we define as the invention of the Greek alphabet, and then spread thereafter. Nor do we know whether it was the idea of alphabetic

[12] Astoreca (2021), p.128, emphasizes that the epichoric scripts served dialectal varieties and it was the emergence of *Koine* in the third century BCE, which was closest to the Ionic script and really marked the Greek alphabet as a unified entity.

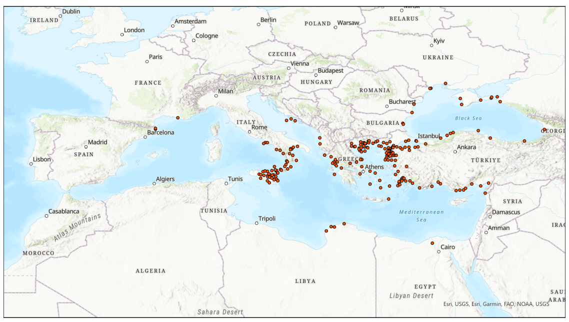
Figure 1: Maps: Cities in the Mediterranean and Black Sea Regions



(a) Cities, Phoenician sites, origins and mines



(b) Cities with Alphabets



(c) Cities with precise coinage dates

(d) Cities with approximate coinage dates

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

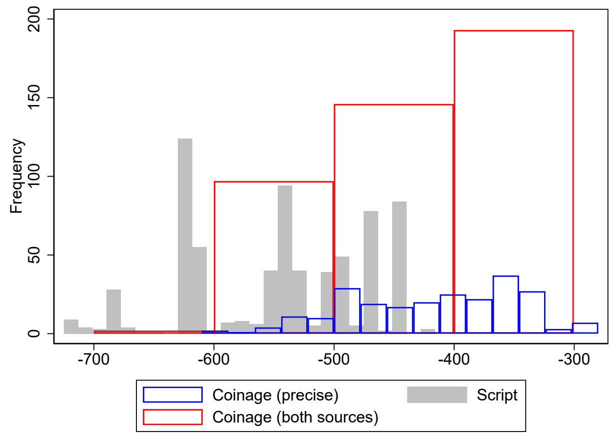
writing that spread directly to different locations giving rise to the many epichoric scripts.[13]

3.3 Intercity Travel Times

Travel times across cities are crucial for our analysis. Spatial diffusion measures, trade potential, and proximity to potential origins of diffusion are based on them. Our imputation of 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

[13]We adopt the term in deference to the classical scholarship Lilian H. Jeffery and Johnston (1990). For more detail, see the Appendix Online and Chen and Ioannides (2026). 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].

Figure 2: Histograms for Dates of Adoption of Alphabetic Writing and Issues of Coinage



Data Lab team, we construct 2737 evenly spaced segments that cover the entire coastline of the Mediterranean and Black Seas. The sailing times for all coastal segment midpoint-pairs are based on wind speeds and parameters from Whitewright (2011).[14] Thus, they are directional (asymmetric). Since our empirical analyses are rich in other dimensions already, for the main specifications we use average travel cost between any two places. However, in the appendix, we report some of our results with directional costs. The coastal segment midpoints are about 15km apart. Further details are given in the Appendix of Chen, Ioannides, and Rauch (2025).[15]

A second component is constructed from overland travel times in the form of walking times which 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 city pairs and the times between each city and their nearest coastal sites.[16] Thus, we account for the differential travel times by defining travel times, in hours, between inland points a and

[14]We are grateful to the Tufts Data Lab and Dr. Takvor Soukissian, Hellenic Center for Marine Research, for their help with the sailing times data.

[15]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).

[16]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.

b as follows:

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

where the parameter γ adjusts upwards the cost of walking (overland) travel relative to maritime travel; A and B denote coastal segments nearest inland cities a and b, respectively. Walking time imputations adjust for the geographical conditions of paths. For results reported in this paper, we use $\gamma = 5$. Alternative traveling cost parameter values $\gamma = 10$, and $= 20$ yield qualitatively similar results with those with the value of $= 5$ and are thus not reported.

4 Empirical analysis

4.1 Modeling the Spatial Evolution of Adoptions of Alphabetic Writing and Minting of Coins

Both alphabetic writing and coinage are likely to have been huge technological shocks at the time. Adoption of alphabetic writing by scribes and educated elites marks the beginning of literacy in the ancient Hellenic world. In addition, coinage, in particular, was part of standardization of measures [Kallet and Kroll (2020)]. Both innovations functioned as TFP shocks, which in the case of writing the economics literature has recognized at least since Ashraf and Galor (2011). Next we introduce empirical models for the spatial evolution of adoption of alphabetic writing or minting of coins as innovations.

Coinage was subject to more complicated forces due to economic, political and military events, but the historical record does not allow us to identify dates of reconsideration of coinage issues.[17] For both innovations we work with the first documented instances for each polis. Whether reconsiderations are allowed would affect the precise analytics of transitional

[17] We owe this point to Jacques Melitz; relatedly, see Grierson (1975).

dynamics of the process and the respective long-run equilibria, but in qualitatively minor ways [Chen and Ioannides (2026)].

We model adoptions as discrete events and study them by organizing the data in a panel structure. That is, for city i that adopts an innovation in period $s,\ 1 \leq s \leq T$, the indicator of adoption $\mathcal{A}_{i,t}$ is coded as follows:

$$\mathcal{A}_{i,t} = -1,\ t < s;\ \mathcal{A}_{i,t} = 1\ \ s \leq t,$$

where we have coded non-adoption with -1 in order to conform to the requirements of model we present below below. Given the one-time decision and the multi-period setting, we consider in each period adoption decisions by cities that have not yet adopted. In other words, we simply exclude from the regressions for later periods cities that have adopted, though the data for the set of *neighbors* that have already adopted are used as source of contextual effects. That is, we assume that the probability that city i adopts alphabetic writing (or coinage) at time t, $\mathcal{A}_{i,t} = 1$, if it had not adopted before, $\mathcal{A}_{i,t-1} = -1$, is written as:

$$\text{Prob}\left[\mathcal{A}_{i,t} = 1 | \mathcal{A}_{i,t-1} = -1\right] = I(B_{i1}(\mathcal{A}_{1,t-1}), ..., B_{ij}(\mathcal{A}_{j,t-1}), ...B_{iJ}(\mathcal{A}_{J,t-1})) + h_i + \epsilon_{i,t}, \quad (2)$$

where the term $I(\cdot)$ in the RHS of (2) denotes the total spatial spillovers on i as a function of $B_{ij}(\mathcal{A}_{j,t-1})$, the effect on i of the interactions with neighbor $j \in \nu(i) := \{1, \ldots, J\};\ h_i$ the contribution of city $i-$specific attributes to the value of adoption, and $\epsilon_{i,t}$ a random shock.

The function $I(\cdot)$ flexibly accommodates spatial spillovers of different types. We start with a linear baseline model for $I(\cdot)$:

$$I(B_{i1}(\mathcal{A}_{1,t-1}), ..., B_{ij}(\mathcal{A}_{j,t-1}), ...B_{iJ}(\mathcal{A}_{J,t-1})) := \sum_{j \in \nu(i)} B_{ij}(\mathcal{A}_{j,t-1}). \quad (3)$$

The effect on i's interacting with $j \in \nu(i)$ is modeled as a function of $j's$ attributes and of the distance, appropriately defined, between i and j. Specifically, we assume that the attribute of j that matters for $i's$ adoption decision is the adoption status of j:

$$B_{ij} = \frac{1}{d_{ij}} \cdot \begin{cases} \alpha, \text{ if } \mathcal{A}_{j,t-1} = 1; \\ \beta, \text{ if } \mathcal{A}_{j,t-1} = -1. \end{cases} \tag{4}$$

That is, the effect of i's interacting with a neighbor that has not adopted is β, rather than zero. There are several reasons for β to be non-zero. Interactions between i and j may be associated with economic activity, such as trade, for which preceding adoption by j is not indispensable, though still valuable for city i.

Given Eq. (4), Eq. (3) becomes:

$$I(\cdot) = \sum_{j \in \nu(i) \cap AD_{t-1}} \frac{\alpha}{d_{ij}} + \sum_{k \in \nu(i) \cap NAD_{t-1}} \frac{\beta}{d_{ik}} = (\alpha - \beta) \sum_{j \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ij}} + \beta \sum_{k \in \nu(i)} \frac{1}{d_{ik}},$$

where AD_{t-1}, and NAD_{t-1} denote, respectively, the set of poleis that have and have not adopted by time $t-1$. Thus, substituting for $I(\cdot)$ in (2) yields:

$$\text{Prob}\left[\mathcal{A}_{i,t} = 1 | \mathcal{A}_{i,t-1} = -1\right] = (\alpha - \beta) \cdot \Big(\sum_{k \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ik}} \Big) + \beta \cdot \Big(\sum_{j \in \nu(i)} \frac{1}{d_{ij}} \Big) + h_i + \epsilon_{i,t}. \tag{5}$$

While $\sum_{k \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ik}}$ is a measure of proximity to previous adopters, we consider $\sum_{j \in \nu(i)} \frac{1}{d_{ij}}$ as a measure of how central city i is in the travel network, proxying for the value of the ease of communication independent of adoption status of other cities. For clarity, we may normalize the distance terms in $\sum_{k \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ik}}$ as $\sum_{k \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ik}} / (\sum_{q \in \nu(i)} \frac{1}{d_{iq}})$. In that case (5) would becomes a typical linear-in-mean model in the social network literature, a Bass diffusion, or Young's contagion model (Durlauf and Ioannides (2010); Bass (1969); Young (2009)).[18]

[18]To see that it is close to a linear-in-means model, we can rewrite $\sum_{j \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ik}} / (\sum_{q \in \nu(i)} \frac{1}{d_{iq}}) = 1/2 \cdot \sum_{k \in \nu(i)} \frac{1/d_{ik}}{\sum_{q \in \nu(i)} 1/d_{iq}} \mathcal{A}_k + 1/2$,with $\sum_{k \in \nu(i)} \frac{1/d_{ik}}{\sum_{q \in \nu(i)} 1/d_{iq}} \mathcal{A}_k$ being the weighted average of neighbors' outcomes. Similarly, this is closely related to the Bass (1969) diffusion or the contagion model in Young (2009).

Reasons for the term $\alpha - \beta$ in the RHS of (5) to be non-zero are: One, acquisition of knowledge, that is, a city gaining more knowledge about the innovation from other cities that have adopted. "A current non-adopter hear[ing] about the innovation from a previous adopter" is an example provided by Young (2009) in favor of a contagion model. Another reason, which is particularly relevant for the issue of coinage, is the potential of "free riding" by which we mean the following. 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 city may "get by" using coins issued by other cities, instead of striking its own. A city could acquire such coinage by trading and maintaining a surplus, or by such violent means as plunder and looting. Thus a negative effect would be implied from the adoption decisions of other cities on a city' own decision to issue coinage. This would be rational because coinage was costly to mint, but it would still serve its functions without a city's incurring the minting cost. Therefore, whether or not minting of coins by other cities discourages a city to mint its own is an empirical question. As adoption of alphabetic writing would not require anything comparable in terms of resources, these arguments apply mainly to coinage.

A richer model is required to capture spillovers that express strategic considerations originating in conformity or complementarity. Intuitively, conformity implies that the value of adopting an innovation increases when a sufficiently large share of neighbors have also adopted, which requires that $I(\cdot)$ be nonlinear. Given the intrinsic value of adoption h_i, city i's decision $\mathcal{A}_{i,t}$ depends on the adoption status of its neighbors, summarized by $\sum_{j\in\nu(i)} b_{ij}\mathcal{A}_{j,t-1}$. By defining $b_{ij} := \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}}$, the term $\sum_{j\in\nu(i)} b_{ij}\mathcal{A}_{j,t-1}$ can be interpreted as the weighted share of neighbors that adopted.[19] Konno and Ioannides (2019) formally

Such a model in continuous time can be written as $\frac{f(t)}{1-F(t)} = p + qF(t)$ where $f(t)$ is the rate of new adoption and $F(t)$ is the share of cities that have adopted. Adapted to discrete time, the left hand side may be interpreted as the share of new adopters conditional on not having adopted yet. A analog to the share of total adopters $F(t)$ on the right-hand side, under our spatial setting, would be $\sum_{k\in\nu(i)\cap AD_{t-1}} \frac{1}{d_{ik}} / (\sum_{q\in\nu(i)} \frac{1}{d_{iq}})$, if we think of it as the weighted average proportion of neighbors that have adopted.

[19]It is a linear transformation of the weighted share of neighbors that adopted: $\frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}}\mathcal{A}_{j,t-1} =$

model a coordination game incorporating strategic behavior of complementarity, which implies a spatial logit response model, and extend it to general topologies. That is, Proposition 6, *ibid.*, section 5.3, extends Brock and Durlauf (2001) to multinomial settings.[20] Following Konno and Ioannides (2019), function $I(\cdot)$ becomes:

$$I(\cdot) = \frac{1}{2}\left[1 + \tanh\left(\zeta \sum_{j\in\nu(i)} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}} \mathcal{A}_{j,t-1}\right)\right], \tag{6}$$

where $\sum_{j\in\nu(i)} \frac{d_{ij}}{\sum_{k\in\nu(i)} d_{ik}} \mathcal{A}_{j,t-1}$ is the share of neighbors that have adopted, weighted by the respective normalized inverse distances.[21] In addition, we allow for potential effects of interactions reflecting other reasons such as trade, and thus redefine $I(\cdot)$ as follows:

$$I(\cdot) = \frac{1}{2}\left[1 + \varphi\cdot\tanh\left(\zeta \sum_{j\in\nu(i)} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}} \mathcal{A}_{j,t-1}\right) + \beta\cdot\left(\sum_{j\in\nu(i)} \frac{1}{d_{ij}}\right)\right],$$

where φ expresses the importance of conformity relative to other factors.

The probability, from (2), that city i that has not adopted as of time t will adopt at time t is now written as:[22]

$$\text{Prob}\left[\mathcal{A}_{i,t} = 1|\mathcal{A}_{i,t-1} = -1\right] = \frac{1}{2}\left[1 + \varphi\cdot\tanh\left(\zeta \sum_{j\in\nu(i)} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}} \mathcal{A}_{j,t-1}\right) + \beta\cdot(\sum_{j\in\nu(i)} \frac{1}{d_{ij}})\right] + h_i + \epsilon_{i,t}. \tag{7}$$

A key advantage of working with (7) is that the function $\tanh(\cdot)$ is a well-behaved, increasing sigmoid function of its argument. Its inherent nonlinearity allows (7) to be considered as

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$2\cdot\sum_{j\in\nu(i)\cap AD_{t-1}} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}} - 1.$

[20]However, an extension of Brock and Durlauf (2001) is necessary for the following reason: the evolution of adoptions by the system of cities is conditional on past *realizations* of neighbors' decisions, while theirs is based on expectations.

[21]Konno and Ioannides (2019) shows that the parameter ζ determines payoff-responsiveness. With extreme value shocks underlying the formulation, ζ is proportional to the inverse of the variance of the shock.

[22]It is implicit that $\text{Prob}\left[\mathcal{A}_{i,t} = -1|\mathcal{A}_{i,t-1} = -1\right] = \frac{1}{2} - \varphi\cdot\frac{1}{2}\tanh\left(\zeta\sum_{j\in\nu(i)} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}}\mathcal{A}_{j,t-1}\right) - \frac{1}{2}\beta\cdot\left(\sum_{j\in\nu(i)}\frac{1}{d_{ij}}\right) - h_i - \epsilon_{i,t}$ and we can summarize it as $\text{Prob}\left[\mathcal{A}_{i,t} = \mathcal{A}|\mathcal{A}_{i,t-1} = -1\right] = \frac{1}{2} + \mathcal{A}\left[\varphi\cdot\frac{1}{2}\tanh\left(\zeta\sum_{j\in\nu(i)} \frac{1/d_{ij}}{\sum_{k\in\nu(i)} 1/d_{ik}}\mathcal{A}_{j,t-1}\right) + \frac{1}{2}\beta\cdot\left(\sum_{j\in\nu(i)}\frac{1}{d_{ij}}\right) + h_i + \epsilon_{i,t}\right]$ for $\mathcal{A} = 1, -1$.

a nonlinear flexible function for spatial autoregressions that accommodate all possibilities discussed above. Intuitively, a weak (strong) effect from previous adoptions and small (large) intrinsic value may make non-adoption (adoption) more attractive.

We simplify notation by treating all other cities as neighbors of i, but weighting them by the respective inverse distances. That is:

$$\mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) := \sum_q \frac{1/\tau_{qi}}{\sum_p 1/\tau_{pi}} \cdot \mathcal{A}_{q,t-1} = \frac{\sum_{k\in Adopter_{t-1}} 1/\tau_{ki} - \sum_{m\in NonAdopter_{t-1}} 1/\tau_{mi}}{\sum_p 1/\tau_{pi}}. \quad (8)$$

This normalized market-access style measure possesses the following advantages. First, it has a spatial attenuation property in that it assigns smaller weights to adoption by cities further away. And second, it allays some of the recent concerns about market access being correlated with overall location; see Borusyak and Hull (2023). Indeed, if we compute the mean of multiple placebo draws for $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ assuming random adoptions, it is almost constant across cities.[23]

4.2 Spatial Diffusion Hypotheses and Estimation

We estimate (5) and (7). In view of (8) and in order to make the two equations readily comparable, we rewrite the former as[24]

$$\mathrm{Prob}\left[\mathcal{A}_{i,t} = 1 | \mathcal{A}_{i,t-1} = -1\right] = \frac{1}{2} + \frac{1}{2} \cdot \left(b_0 + b_1 \ \mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) + \mathcal{X}_i \boldsymbol{\beta} + \mathrm{Period}_t\right) + \epsilon_{it}, \quad (9)$$

and the latter may in turn be written as:

$$\mathrm{Prob}\left[\mathcal{A}_{i,t} = 1 | \mathcal{A}_{i,t-1} = -1\right] = \frac{1}{2} + \frac{1}{2} \cdot \left(a_0 + a_1 \ \tanh\left[c_1 \ \mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) + c_0\right] + \mathcal{X}_i \boldsymbol{\beta} + \mathrm{Period}_t\right) + e_{it}. \quad (10)$$

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

[24] Nothing changes excepts that the magnitude of the coefficients is halved if we estimate $\mathrm{Prob}\left[\mathcal{A}_{i,t} = 1\right] = b_0 + b_1 \mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) + \mathcal{X}_i \boldsymbol{\beta} + \mathrm{Period}_t + \epsilon_{it}$.

We underscore that the organization of the data and the design of the estimation incorporates the notion that once a city has adopted it is not reconsidering its decision. In other words, in each time period our regressions use observations for only those cities that have not adopted by $t-1$. As discussed previously, $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ captures the differential effect of interacting with previous adoptions relative to non-adopters. $\mathcal{X}_i$ is a vector of time-invariant variables that includes a measure of each city's location in the travel network and other factors, as we detail below. Period fixed effects, denoted by Period_t, are important: as more cities adopt over time, the adopters become spatially denser, and $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ will grow larger for all cities. Therefore, allowing period fixed effects makes our estimation "within period." We control for spatially correlated shocks by also including terms like $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ but defined in terms of the geographical "crow-flies" distances, that is, not travel times between cities.

We estimate both probability models with maximum likelihood.[25] We aim to capture the effect of spatial spillovers by including a comprehensive vector of time-invariant control variables $\mathcal{X}_i$ that may otherwise be confounding factors. The effects of some of those variables themselves are also interesting, and we explore them in section 4.4.

As the previous section shows, it is crucial to control for the overall location in the travel network. Therefore we include in $\mathcal{X}_i$, Eq. (9) and Eq. (10), the sum of inverse distances to all other cities, which is a common measure of market access. It captures the common effect of interacting with both adopters and non-adopters, and there are two major possible mechanisms for such an effect to exist: trade and competition.

Trade contributes to the accumulation of wealth and thus to a city's incentives to adopt innovations. Trade may also affect the demand for both technologies, as both alphabetic writing and coinage could lower transactions and communications costs. In the case of coinage, since precious metals are required to mint coins, competition among cities is an additional factor. While proximity to other cities can affect access to precious metals via trade, it can also imply more competition. More centrally located cities have access to

[25] We may also write out the expectations in each case, and estimate them with OLS and nonlinear least squares. Those results are very similar and are not reported here.

a greater number of other cities and can potentially get precious metals from them. Yet that may come with competition in more densely settled regions with a greater number of neighboring cities. Unlike centrally located cities, cities in remote locations are less likely to avail themselves of mutual coincidence of wants for tradeables which would make them more dependent on own coinage. Comin and Hobijn (2004) also find that the degree of openness to trade matters for technology adoption.

While unfortunately we do not have actual trade data, evidence suggests that long-distance trade existed; see Izdebski et al. (2020) and Chen, Ioannides, and Rauch (2025) for related discussion. Being central in the travel network is a proxy for trade potential (Chen and Ioannides (2026)). As a robustness check, we replace the sum of inverse distance measure with eigenvector centrality, based on an adjacency matrix defined in terms of inverse intercity travel times, i.e., $[\mathbf{T}_{ij} = 1/\tau_{ij}]$, as it is commonly done in network theory; see Bloch, Jackson, and Tebaldi (2023).[26] It is a pure measure of connectedness and therefore a measure of interaction.[27] Our results barely change and thus results with eigenvector centrality are not shown.

We also control for local microgeographic variables. Specifically, we use the available geographic coordinates to merge the data of ancient cities with microgeographic information such as ruggedness, malaria index, temperature, precipitation, and elevation characterizing the segments (discussed in Section 3.3) in which they lie. The ruggedness index is from Nunn

[26]The eigenvector centralities are the components of the eigenvector associated with the Perron-Frobenius eigenvalue for the adjacency matrix.

[27]We note that for an adjacency matrix thus defined, its right eigenvector centrality is very similar to the commonly used market access measure. To see this we may write in non-matrix form: $EV_i = \lambda \sum_j (1/\tau_{ij}) * EV_j$. Not surprisingly, eigenvector centrality and market access measures are highly correlated. Eigenvector centrality has a theoretical foundation in the trade and economic geography literature. Loosely speaking, it proxies for city i income. In the economic geography model of Allen and Arkolakis (2014) with goods being differentiated by origin and all cities trading with all other cities, intercity travel times and city locations along with their microgeographic characteristics relevant to productivity define fully the economic geography of the system of trading cities. While we eschew here full development of a model, we note that in such a model the right and left eigenvectors of a suitably defined homogeneous linear system characterize fully a trading economy at spatial equilibrium. Within that model, the right eigenvector has a very specific interpretation: it is proportional to the product of the city i wage rate raised to the power of the elasticity of substitution of the underlying preference structure times city i population. As Allen and Arkolakis (2025) argue, more central locations in terms of travel costs are more likely associated with greater economic activity. The eigenvectors $\tilde{\mathbf{x}}$ and $\tilde{\mathbf{y}}$ of the matrix of inverse travel times $\mathbf{T}$ may be interpreted as proxies of centrality.

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.[28]

It behooves us to account for such political economy considerations as cities' memberships in the Delian League and in regional federations (known as *Koinon*). Such memberships were directly relevant for the adoption of innovations, as members' decisions were likely affected by trade regulations, collaborations, sharing of resources and common shocks.

Membership in the Delian League was arguably less of a choice, as it was forced on cities by Athens in its geopolitical pursuits. Most regional federations were more likely outcomes of choice by cities. Due to endogeneity concerns, we do not include membership in the Delian League and in regional federations in our main specifications, but explore their effects only in the subsection 4.4.[29] The Delian League was the largest, best known and longest lasting of often-shifting alliances.[30] While it lasted, it dominated the ancient Greek world as a military, economic, coinage, and standards of measurement union under the hegemony of Athens [Kallet and Kroll (2020)]. Unlike the Delian League, many regional city federations existed and were rather loose associations.[31] In addition, for cities that were colonies of other cities, their decisions might have been influenced by the adoption decisions of their colonizers.[32]

Another set of time-invariant spatial factors that are potentially important are proximity to potential origins for both innovations and to mines for coinage. Therefore, the effect on

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

[29]But we do note that, while not shown, the inclusion of those two variables has minimum impact on the estimated coefficients of $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$.

[30]It was founded in 478 BCE and dissolved in 404 BCE. Its membership varied between 150 and 300 cities.

[31]Among them, the Peloponnesian League under Sparta's influence was best known. These less well known associations comprised of several cities 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.*The regional federations became unimportant after 300 BCE; see MacKil (2013); Economou, Kyriazis, and Metaxas (2015).

[32]Our data do not allow a full exploration of these issues. The indicator of being a colony is highly correlated with whether a city's colonizer minted coins or adopted alphabetic writing. Colonization was most likely not just a reaction to population growth, but exploratory entrepreneurship and geopolitical events, such as the Persian invasions, played a big role. See Hansen and Nielsen (2004), pp. 150-153.

i of interacting with j , B_{ij}, depends, in addition to j's adoption status, on whether city j functioned as an origin for diffusion, or was near mines:

$$B_{ij} = \frac{1}{d_{ij}} \cdot \big(\beta + (\alpha - \beta) \cdot \mathbb{1}\{\mathcal{A}_{j,t-1} = 1\} + \gamma_1 \cdot \mathbb{1}\{\text{j is an origin}\} + \gamma_2 \cdot \mathbb{1}\{\text{j has a mine}\}\big). \quad (11)$$

The total spatial spillover effect $I(\cdot)$ includes the sum of inverse distances to the set of origins, $\mathcal{M}_o$, and the sum of inverse distance to the set of mines, $\mathcal{M}_m$:

$$I(\cdot) = \big(\alpha - \beta\big) \sum_{j \in \nu(i) \cap AD_{t-1}} \frac{1}{d_{ij}} + \beta \sum_{k \in \nu(i)} \frac{1}{d_{ik}} + \gamma_1 \sum_{k \in \mathcal{H}_o} \frac{1}{d_{ik}} + \gamma_2 \sum_{k \in \mathcal{H}_m} \frac{1}{d_{ik}}.$$

We deal with the case that i itself is an origin or nearer a mine, by computing:

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

For alphabetic writing, we consider as potential origins not only cities but also sites that scholars think are likely to have been where the invention and diffusion of alphabetic writing in the ancient Greek world originated. Specifically, Eretria (and nearby Lefkandi, a site) is directly linked to early transmission of the Chalkis/Kyme (Euboean) alphabet 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 cities in Crete are also mentioned, for which the location of modern Herakleion, not a city in the relevant period but a harbor, may proxy.[33] Rhodos[34] is one such potential origin in its own right as well as a proxy for coastal cities and sites in the Middle East, including all of the Phoenician city states, and of course sites in Cyprus,[35] which is known to

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

[34] A city after 408/7 BCE that was formed via *synoecism* by nearby Ialyssos, Kamiros and Lindos [Hansen and Nielsen (2004)]. The latter three cities are attested to have hosted bilingual communities of Greek and Phoenician traders.

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

have hosted bilingual communities of Greek and Phoenician speakers, all of which lie to the east of Rhodos. Gabii, a site in Italy, is also attested with the Eretrian alphabet, a version of the Euboean alphabet, at an early date. In addition, we consider the potential effect of proximity to 30 Phoenician colonies.[36]

Regarding coinage, Sardis, a prominent non-Hellenic city-state in ancient Lydia. is known to have minted coins first, and originally in electrum, in that part of the world (but possibly globally; see Schaps (2004)). We define as mines a group of sites that are attested with evidence of ancient mining of relatively high-quality silver and gold deposits and of cities that are known to have issued coinage early, or were close to known mines of precious metals. We rely on the literature that we have already cited and, in addition, Vaxevanopoulos et al. (2022). The group of cities includes Amphipolis, Ilion, Lampsakos, Phokaia, Thasos, and Thera. We also use data for several additional sites with mines that are attested to have been used in the relevant historical period.[37] See Figure 1a for a map with the locations of those sites.

Using the sum of inverse distance method discussed above, we define *MA:Potential Origins*, which includes the cities and sites listed above as potential origins for script, and *MA:Phoenician Sites*, which is defined over known Phoenician colonies. The variable *MA:Mines* is defined over cities close to mines and sites with mines themselves, based on Vaxevanopoulos et al. (2022). In section 4.4 we test the overall importance of proximity

[36]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 cities, including 13 entries for Athens and its port Piraeus, 7 for Rhodos 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).

[37]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.

to those groups of cities and sites.[38] For consistency of interpretation, although Sardis is a single city, 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).

As briefly noted above, we also include in $\mathcal{X}_i$ variables that are meant to capture potential spatially correlated shocks. For example, if in some period a region experienced very beneficial climatic variation, cities there would have grown and accumulated more wealth, and therefore found it advantageous to adopt alphabetic writing. In that case, we would expect nearby cities to behave similarly because of spatially correlated shocks rather than spatial spillovers. We control for this potential source of spatial correlation by distinguishing between travel distance and geographical distance ("crow-flies" distance) between cities, and by also controlling for proximity in terms of the latter. [39] Arguably, having controlled for geographical distance, travel distance only matters because it affects interactions among cities.

4.2.1 Definitions of Testable Hypotheses

We organize our empirical analysis by testing the following six hypotheses:

H_0 : *Direct Spread of Innovation.*

If true, the spread of each innovation is exogenous, originating at some site(s) and occurring at roughly the speed of travel in that part of the world. MA($\mathcal{A}_{\nu(i),t-1}$) should be insignificant, while MA(potential origins) for alphabetic writing and MA(Sardis) for coinage should have positive effects, controlling for micro-geographic characteristics.

H_1 : *Exogenous and Sequential Spread of Innovation.*

If true, the spread of innovation is sequential as knowledge of invention leads to innovation which spreads exogenously. MA($\mathcal{A}_{\nu(i),t-1}$) should have at least a positive linear effect. Thus,

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

[39] 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.

b_1 in (9) and a_1 and c_1 in (10) should be significant and have the same sign.

H_2 : *Conformity.*

If true, $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ should have a positive and possibly a nonlinear sigmoid effect. Thus, a_1 and c_1 in (10) should be significant and have the same sign, and $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ should have no significant level effect.

H_3 : *Free-riding.*

If true, $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ should have a negative effect; Thus, b_1 in (9) should be negative, or a_1 and c_1 in (10) to have opposite signs.

H_4 : *Adoption driven by correlated geographical shocks.*

If H_4 is true, b_1, and c_1 should be be zero, and the coefficients for the geographical distance-based counterpart of $\text{MA}(\mathcal{A}_{i,t-1})$ should be significant.

H_5 : *Adoption driven by polis size due to spurious correlation originating in urban hierarchy, when it exhibits spatial patterns.*

If H_5 is true, we should expect $b_1$and c_1 to be significant, when size is not included, and insignificant when it is.

4.3 Estimation Results

We conduct the empirical analysis of spatial diffusion of alphabetic writing by grouping the entire span of available data into centuries.[40] With only few adopters in the late eighth century BCE, we group 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 by breaking the entire length of the study into three periods: late seventh and sixth, fifth, and fourth centuries BCE. The

[40] A major reason for this is the nature of the data. For coinage, we have two sources of data, one in terms of centuries and another in terms of years. Organizing the data into centuries allow us to utilize both sources of data together. For alphabetic writing, although we do not have two sources of data, we have two types: city and regional. Unless a city has its own individual alphabetic writing beforehand, we assume all cities linked to a region adopt the regional Alphabet at the same time, which is not a strong assumption when the period is a century.

numbers of coinage issuers are 66, 157, and 201, respectively. In Table 1, we report summary statistics.

Table 1: Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
MA(Alphabet(t-1))	1,151	-.37	.24	-.74	.5
MA(Coin(t-1))	1,499	-.71	.16	-.92	-.3
Overall MA	894	5.3	1.5	1.6	8.4
MA(Phoenician)	894	.078	.026	.031	.2
MA(Alphabet Origins)	894	.032	.022	.0013	.31
MA(Sardis)	894	.0039	.0026	.0015	.038
MA(Mines)	894	.12	.066	.03	.44
Size	894	2	1.2	1	5
Delian	890	.3	.46	0	1
Koinon	890	.23	.42	0	1

Notes: For $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$, we report the summary statistics based on the pooled sample used for pseudo-panel regressions. For the time-invariant variables, we report the summary statistics for the cross-sectional sample. .

Table 2 reports the estimation results using average travel times over both directions. Columns 1 and 2 report estimation results with a linear specification of equation (9), where $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ enters linearly; columns 3 and 4 those with a discrete choice model, where $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ enters via the hyperbolic tangent specification as in (10). We note that in interpreting the results for $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ with the hyperbolic tangent specification, we must consider the estimated coefficients a_1 and c_1 jointly. When a_1 and c_1 have the same sign, either positive or negative, they imply a positive effect.[41] In all specifications, the linear and quadratic terms of the crow-flies distance-based $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ are used to control for correlations in climatic conditions. Interestingly, $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ is not significant with the linear specification, for either alphabetic writing or coinage, but it is significant for the nonlinear specifications involving the hyperbolic tangent $\tanh(\cdot)$. It is strongly significant and positive in the hyperbolic tangent specification for alphabetic writing, but insignificant for coinage. Comparing the results in columns 1 and 2 with 3 and 4, respectively, suggests

[41] This follows from the properties of the hyperbolic tangent function: $\tanh(-x) = -\tanh(x)$, or $\tanh(x) = -\tanh(-x)$. Thus, $a_1 \tanh\left[c_1 \mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) + c_0\right] = -a_1 \tanh\left[-c_1 \mathrm{MA}(\mathcal{A}_{\nu(i),t-1}) - c_0\right]$.

that nonlinearity is important for alphabetic writing.

Table 2: Spatial Diffusion: Impact of Proximity to Previous Adopters

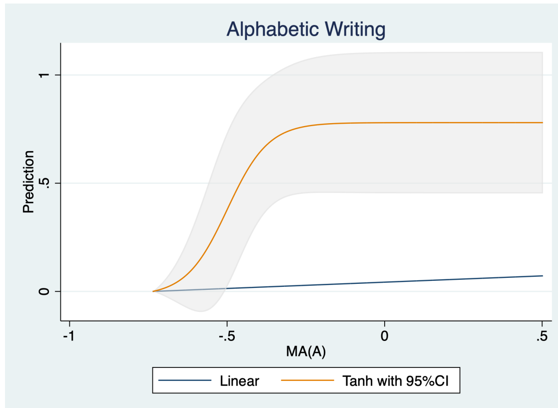
	Linear		Tanh	
	(1) Writing	(2) Coin	(3) Writing	(4) Coin
MA($A_{i,t-1}$)	0.116	1.571	-7.655***	-0.0482
	(0.721)	(1.271)	(2.301)	(0.0390)
Constant	-0.181	0.0423	-3.822***	-0.0241
	(0.818)	(0.939)	(1.062)	(0.0289)
a1			-0.801***	-32.56
			(0.193)	(.)
AIC	1341.20	1582.27	1293.07	1582.27
Inflection Pt			-0.50	-0.50
Obs	1151	1499	1151	1499
N(A=1)	410	358	410	358
ML Iteration Ct	8	6	81	15000

Notes: Pseudo panel maximum likelihood regressions. The maximum iteration count is set as 15,000 and reaching that number implies convergence is not achieved. Columns (1) and (2) are results for regressions linear in MA($A_{i,t-1}$). Columns (3) and (4) are results for regressions with hyperbolic tangent specification. In all specifications, the linear and squared terms of the MA($A_{i,t-1}$) measured in terms of crow-flies distances are controlled for. Market access to all cities, 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 alphabetic writing 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

We examine the performance of tanh(·) by plotting its values using our estimates for MA($\mathcal{A}_{\nu(i),t-1}$). Figure 3 plots the estimated relationship and the associated confidence intervals, as functions of MA($\mathcal{A}_{\nu(i),t-1}$) for the observed range for alphabetic writing, as reported in Table 2. We observe substantial nonlinearity and a pronounced sigmoid pattern. The 95% confidence interval does not fully encompass the straight line implied by the linear model.

We also employ the standard model comparison approach by means of the Akaike Information Criterion (AIC) values for the linear and hyperbolic tangent specifications. AIC balances goodness of fit with model complexity (number of parameters) and is computed based on the log likelihood. The AIC values are reported at the bottom of Table 2. As we can see, the AIC for alphabetic writing with the hyperbolic tangent specification is substantially smaller than that for the linear specification (1293 versus 1341). Not surprisingly, this

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



Notes: Estimation based on Table 2. The confidence interval is computed using the delta method.

is not the case for coinage, for which as we saw previously the hyperbolic tangent specification performs poorly.

These results allow us to conclude in favor of H_2 over H_1. Spatial spillovers are present in the adoption of alphabetic writing only, and not of coinage, and more likely due to conformity rather than mere sequential spread of knowledge. As for coinage, the zero net effect might come from coexistence of negative, due to free-riding, and positive effects.

4.3.1 Robustness Checks

In the main estimations we control for the crow-flies distance based $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ in order to capture spatially correlated shocks that are due to the weather and depend on physical distance. However, one may be concerned about potential multicollinearity between the crow-flies and travel distance-based $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ terms. To alleviate such concern, we carry out estimations by excluding the crow-flies distance-based $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$. The fact that the results barely change, as may be verified by comparing Table 3 with Table 2, allows us to conclude against H_4.

As an additional check, we estimate the model using the directional travel times, that is, separately, *From* city i *To* city j, and *To* city i *From* city j, instead of the average ones. The results are reported in the Appendix, Table A.1. We find that although the results are qualitatively similar to those with average travel times, the effect of positive spatial spillovers is stronger in magnitude when *From* times are used. We interpret this finding as suggesting deliberate action by a city, which is consistent with a strategic element in conformity behavior.

Size is an important control variable, in principle. In our data from the *Inventory,* size is a measure of city *city territory.* As we detail in section 3.1, it proxies for state capacity, which matters for the adoption of both innovations, though likely more of coinage. State capacity and knowledge of metal technology are much more important for coinage and proxied by size. Conceivably, the size distribution of cities may display spatial patterns due to the urban hierarchy, which may interfere with our ability to identify spatial spillovers. To demonstrate, suppose that adoption is driven purely by city size. The largest city adopts alphabetic writing first, followed by the second largest and so on. If the urban hierarchy exhibits spatial dispersion, then the second largest city is likely farther away from the largest city. In such a case, we may infer that being close to previous adopters has a negative effect, but that would not be associated with spillovers. This possibility can be examined for by including a city's own size as a control variable. We are cautious about including city size in our main specification because of endogeneity concerns due to reverse causality: adoptions of innovations function as positive TFP shocks that on their own promote growth. As Table 3 shows, our results are not sensitive to the inclusion of city size.

4.4 Role of Time-Invariant Factors on Dates of Adoption: Location in the Travel Network and Distances to Origins

Having established in the previous section the importance of spatial diffusion of adoptions, a time-varying variable, we now turn to some key time-invariant variables. They include travel network centrality and, in addition, distances from potential origins of the diffusion of alphabetic writing, and from Sardis and known mines for coinage, and city size for both, as discussed in previous sections. We examine their their relative importance as explanatory variables for the spatial diffusion of adoptions by means of Shapley decompositions along the

Table 3: Robustness Check for Spatial Diffusion: the Impact of Proximity to Previous Adopters

	Linear		Tanh	
	(1)	(2)	(3)	(4)
	Writing	Coin	Writing	Coin
Panel A: Control for Size				
MA($A_{i,t-1}$)	-0.278	1.114	-10.26***	-0.216
	(0.695)	(1.102)	(2.743)	(0.210)
Constant	-0.109	-0.793	-5.071***	-0.0327
	(0.846)	(0.716)	(1.362)	(0.141)
a1			-0.709***	-5.051
			(0.169)	(.)
AIC	1299.79	1418.04	1254.24	1418.08
Inflection Pt			-0.49	-0.15
ML Iteration Ct	8	7	68	15000
Panel B: Without Crow-Flies Terms				
MA($A_{i,t-1}$)	0.627	0.409	-7.720***	-0.0887
	(0.538)	(0.762)	(1.891)	(0.165)
Constant	-0.292	-0.650	-3.977***	-0.0103
	(0.699)	(0.890)	(0.941)	(0.192)
a1			-0.787***	-4.626
			(0.144)	(.)
AIC	1370.78	1584.75	1294.97	1584.75
Inflection Pt			-0.52	-0.12
Obs	1151	1499	1151	1499
N(A=1)	410	358	410	358
ML Iteration Ct	6	5	64	15000

Notes: Pseudo panel maximum likelihood regressions. Columns (1) and (2) are results for regressions linear in MA($A_{i,t-1}$). Columns (3) and (4) are results for regressions with hyperbolic tangent specification. In all specifications, the linear and squared terms of the MA($A_{i,t-1}$) measured in terms of crow-flies distances are controlled for. Market access to all cities, 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 alphabetic writing 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

lines of Huettner and Sunder (2012) and Henderson et al. (2018). The latter is more closely related to our application.

Table 4 reports the estimates for the role of location in the network (Overall MA) and the proximity variables defined in the market-access format according to 4.2. Again, since results excluding and including city size are very similar, here we only report results with city size included. Panel A shows results for adoption of alphabetic writing and panel B shows results for coinage. Columns 1 and 2 report results with exactly the same specifications as in Table 2. We also compare them with specifications that do not include the diffusion variables, which are reported in column 3.

We perform robustness checks in the form of survival regressions, reported in column 4, rather than pseudo-panel regressions, in order to clarify the effects of the time invariant variables. Survival regressions lend themselves conveniently to accommodating censored endogenous variables, which is the case for both alphabetic writing and coinage. The spatial diffusion of adoption variables are not included in the survival regressions, as these are in effect cross-sectional specifications. The dependent variable is 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, that is earlier adoption.

The effects of the time-invariant variables are consistent across specifications. Location in the network (Overall MA) has a strong and positive effect for adoption of alphabetic writing. This accords with intuition regarding the role of trade. Trade provides cities an incentive to adopt the technology of writing, which facilitated record keeping and ensured greater transactions efficiency. However, when we do not control for $\mathrm{MA}(\mathrm{A}_{\nu(i),t-1})$, as in columns 3 and 4, Overall MA is not significant. This suggests that even if we were interested in the effects of time-invariant factors only, ignoring spatial diffusion of adoption could lead to

Table 4: Spatial Diffusion: the Impact of Time-Invariant Variables

	Linear	Tanh	w/o MA(D)	Survival
	(1)	(2)	(3)	(4)
Panel A: Regressions for Writing				
MA(Phoenician)	1.798	1.270	0.960	-3.606
	(2.661)	(2.778)	(1.778)	(3.842)
MA(Origins)	-2.556	-1.870	5.936***	10.31
	(7.128)	(6.105)	(1.538)	(7.131)
Size	0.141***	0.126***	0.0797***	0.136**
	(0.0323)	(0.0277)	(0.0207)	(0.0538)
Overall MA	0.150***	0.143***	0.0540	0.0700
	(0.0568)	(0.0463)	(0.0426)	(0.0513)
Obs	1151	1151	2045	894
Delian	0.0558	0.0859	-0.250**	-0.323**
	(0.123)	(0.113)	(0.105)	(0.131)
Koinon	0.445**	0.515***	0.348*	0.299
	(0.193)	(0.198)	(0.186)	(0.187)
Obs	1143	1143	2033	890
Panel B: Regressions for Coinage				
MA(Sardis)	-3.668	-3.676	-2.342	34.10***
	(4.785)	(4.780)	(5.300)	(9.765)
MA(Mines)	1.711**	1.716**	1.273***	1.827**
	(0.750)	(0.747)	(0.456)	(0.726)
Size	0.258***	0.258***	0.192***	0.305***
	(0.0224)	(0.0224)	(0.0158)	(0.0301)
Overall MA	-0.0937***	-0.0938***	-0.0487***	-0.106***
	(0.0268)	(0.0268)	(0.0174)	(0.0301)
Obs	1499	1499	2393	894
Delian	0.0298	0.0296	0.188***	0.154**
	(0.0561)	(0.0562)	(0.0439)	(0.0701)
Koinon	0.0949*	0.0948*	0.0181	0.283***
	(0.0563)	(0.0563)	(0.0482)	(0.0758)
Obs	1491	1491	2381	890

Notes: Pseudo panel and survival regressions. Columns (1) - (3) are pseudo panel maximum likelihood regressions, and controls for the linear, the hyperbolic tangent, and no term of MA($A_{i,t-1}$), respectively. In Columns (1) - (2), the linear and squared terms of the MA($A_{i,t-1}$) measured in terms of crow-flies travel times are also controlled for. Column (4) is survival regressions where the starting dates are assumed to be one year before the earliest observed years in our data for alphabetic writing and coinage. The survival regressions does not include MA($A_{i,t-1}$). 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. City size, geographical variables are included in all specifications. Panel A has adoption of alphabetic writing as the outcome while panel B has coinage as the outcome. The coefficients for overall MA, proximity (MA) and size are from specifications without Delian and Koinon. Coefficients for Delian and Koinon come from separate regressions that are identical to the above specification expect for adding the two variables as additional variables. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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 the diffusion of alphabetic writing, which is again significant only when the spatial diffusion variables are not controlled for. City size has a positive effect on adoption, possibly reflecting the positive effect of state capacity that it proxies for.

For coinage, how central a city is in the network has a negative and strong effect, which is totally different than for alphabetic writing, We offer several possible explanations. One is that it reflects properties of the urban hierarchy. While we do not report it, our examination of the data suggests Overall MA is negatively correlated with size, meaning that more centrally located cities are on average smaller, while some larger cities are typically located at the periphery of the study area.[42] While not reported here, we find that compared with the specification without size, the specification that includes size shows city overall market access with much smaller coefficients. However, the negative effects persist even when size is included. Another possible explanation is competition over access to resources for coinage, namely precious metals. Being surrounded by more cities may imply stronger competition. Yet another possible explanation for the negative effect of central location on coinage issue is that less centrally located cities are more likely to depend on own coinage for trade as they are less likely to benefit from mutual coincidence of wants (or opportunities to barter) in trade. Proximity to mines has, not surprisingly, a strong and positive effect in all specifications. Size again has positive and significant effects, and the respective regression coefficients for coinage are much larger than for the alphabetic writing regressions. This confirms that state capacity is more important for issuing coinage than for the adoption of alphabetic writing.

The fact that according to the totality of the historical evidence coinage did originate

[42]Larger cities at the periphery included Syrakousai (Suracuse) and Rhegion, both in Italy, Rhode in Spain, but also Ephesus, in Turkey, Korkyra (Corfu) in the Ionian Sea, and Rhodos in in the Eastern Aegean Sea, both in Greece.

in Sardis warrants an investigation of how travel times from Sardis and travel times from known mines compare as explanatory variables in the dynamics of the diffusion of coinage issue. The estimated effect of $\mathrm{MA}(\mathrm{Sardis})_i$ is negative and insignificant, when size is included but significant when size is not included (not shown). This is noteworthy and likely suggests presence of a sphere of influence of Sardis: being nearer to it discourages coinage issue, all other things being equal. Proximity to mines, on the contrary, has a positive and significant effect. We also note that while not shown, excluding $\mathrm{MA}(\mathrm{Sardis})_i$ or $\mathrm{MA}(\mathrm{Mines})_i$ has a minimal effect on the coefficients of other variables.

We do not consider the potential effects of a city's membership in the Delian League and in regional federations (Koinon) in the main specification due to endogeneity concerns, but do discuss them here. The bottom two rows of panels A and B, Table 4, report the effects of the Delian League and regional federations memberships. We note (but suppress the details for reasons of brevity) that controlling for Delian League and Koinon memberships barely changes the effect of $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ and of time-invariant variables. Interestingly, Delian League membership has significant effects only when the diffusion variable $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ is not included, as reported in columns 3 and 4. On the contrary, membership in regional federations has persistent positive effects on alphabetic writing adoption across specifications. This could be due to the fact that members of regional federations experienced a greater need to communicate with other members, and thus stronger incentives to adopt alphabetic writing. This is in contrast to the members of the Delian League, which availed themselves of the benefits associated with its being also a standards union.

Coinage decisions might be influenced by whether a city had been founded as colony of other cities. While not reported due to space limit, we do find that a city's being a colony has a positive and very significant effect in a regression like the one reported in column 1, Table 2. A positive and very significant effect is also estimated for a dummy variable indicating that a city's colonizer had minted coins. However, the respective indicators are highly correlated (0.88) and may not be included together in the regression.

Table 5: Spatial Diffusion: Shapley Decomposition

	(1) Script	(2) Coin	(3) Script	(4) Coin
MA(adopters) (Travel cost)	25	19	23	7.3
MA(adopters) (crow-flies cost)	22	16	20	6.1
Local geographical variables	34	28	34	9.4
Overall MA	11	20	11	4.9
Phoenician(Script)/Sardis(Coin)	.42	2.6	.42	.52
Origins(Script)/Mines(Coin)	1.6	5.7	1.5	1.6
Period FE	5.8	9.1	5.3	4
Size			4.9	66

Notes: Shapley decomposition of the total regression R2 for the OLS regression with linear, 3rd, and 5th order terms of the travel-cost based MA($A_{i,t-1}$), while all the control variables being the same as in Table 2.

Next we compare the relative importance of the time-invariant variables and the (lagged) spatial diffusion variables by means of Shapley decomposition exercises. Since substantial nonlinearity was observed, we include the linear, 3rd, and 5th order terms of MA($A_{i,t-1}$) to mimic the shape of a hyperbolic tangent function. The results are reported in Table 5. For both alphabetic writing and coinage, the local geographical variables play the most important role (when city size is not included), followed by the lagged spatial diffusion variables, network location, period fixed effects, proximity to potential origins of diffusion and mines of precious metals, and proximity to Phoenician colonies and Sardis. City size plays a relatively small role for alphabetic writing, suggesting that scale is not important. It is a very important one for coinage, dwarfing the effects of other variables. When size is included, it alone accounts for 66% of the overall R^2 for coinage. We report in the appendix the Shapley decomposition results with the asymmetric (directional) travel times, which turn out to be qualitatively very similar to those with symmetric travel times.

4.4.1 Summary of Main Results

We may summarize the results reported so far by referring to our baseline hypotheses defined above as follows. Regarding H_0, we conclude that it is rejected — the innovations spread much slower than the speed of travel. In terms of time to travel, it takes less than a month for any city in our sample to reach Sardis, and it takes less than 5 months for any city to reach the farthest potential origin of alphabetic writing. However, it takes centuries, for both coinage and alphabetic writing to be adopted by the majority of cities.

Regarding H_1, we conclude that it is rejected and empirical evidence is in favor of H_2 for spatial spillovers from adoption of alphabetic writing, though not for coinage issue. Regarding nonlinearities in the estimated effects, we note that for alphabetic writing, the sigmoid effect supports the conformity hypothesis: the inflection point is estimated to lie in the range (-0.53 — -0.44). As for H_1, the significance of the linear $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ under *To-travel* supports diffusion of knowledge. H_3 is rejected for alphabetic writing, as market access to previous adopters is always positive. As for coinage, the fact that the coefficient for market access is not significantly different from zero may be viewed as evidence of the net outcome of positive and negative effects. H_4 is rejected for alphabetic writing, since the travel-cost based market access to previous adopters is positive and significant even when the geographical-distance based market access is also controlled for. The fact that the significance and the magnitudes of the coefficients of $\text{MA}(\mathcal{A}_{\nu(i),t-1})$ barely change with and without city size as a control variable rejects H_5, the spurious spatial pattern due to size hypothesis.

Additionally, the effect of being central in the network is positive and significant for alphabetic writing, but negative and significant for coinage. We interpret this finding as evidence that less central, more remote locations are in greater need of coinage. Market access (based on travel times) to origins for alphabetic writing is not significant for neither Phoenician sites nor origins. The fact that city size explains so little of the diffusion of alphabetic writing suggests that its diffusion was more even over space and not accelerated by size. For coinage, access to Sardis is not significant, suggesting a subtle effect due a sphere of influence, but access to mines is significant and positive.

4.5 Interdependence of Adoption of Alphabetic Writing and Coinage Issue Decisions

The results reported so far demonstrate that spatial factors are important for the adoption of both technologies when they are considered on their own. However, since both technologies are investigated, one may wonder how the adoption of one of those innovations may impact the adoption of the other.

In our data, alphabetic writing was adopted by most cities earlier than coinage.[43] We thus examine the impact of the former on the latter. There could be a positive effect if adoption of alphabetic writing operates as a TFP shock, contributing to city growth which in turn promotes coinage issue.[44] Another possible mechanism, which we owe to a conjecture in Pappa (2019), suggests a negative effect: literacy by having facilitated establishment of trade credit might have even obviated the need of coinage in trade and thus delayed its adoption.[45]

In this context, we take advantage of the knowledge gained in the previous sections and examine whether spatial factors might have played important roles as omitted variables. E.g., a more centrally located city may have acquired 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 city 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 by

[43] The count of the number of cities by alphabetic writing adoption and coinage issue status and dates shows that there exist only 22 cities that adopted alphabetic writing later than issued coinage. The dates coincide for 9 cities. In view of these numbers, the fact that greater measurement error is probably more likely in the alphabetic writing data — writing on perishable media could be a culprit — and the need for organizing the data in a way suitable for estimation justifies the shortcut of studying the impact of alphabetic writing on minting of coins, and not both processes as a vector autoregression, along the lines of Honoré and Kyriazidou (2000) and later works. Data availability is also an issue See Online Appendix, Supplementary Data.

[44] Ashraf and Galor (2011) also recognize writing as a TFP shock.

[45] Barjamovic et al. (2019) rely on data from Assyrian cuneiform tablets as evidence of correspondence among traders abou transcactions that were conducted in the absence of coinage.

inherent interdependence with alphabetic writing having a causal effect on coinage.

Working again with the data arranged in a panel structure, we consider a staggered difference-in-differences 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 cities according to adoption of alphabetic writing and issue of coinage and on the definition of periods are provided in the online appendix. We estimate the following equation:

$$Coin_{it} = \beta \, \mathbf{1}[t \geq TimeAlphabetic_i] + \xi_i + \gamma_t + \varepsilon_{it}, \tag{12}$$

and compare the estimated coefficients β when the spatial diffusion variable $\mathrm{MA}(\mathrm{Coin}_{\nu(i),t-1})$ is and is 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 6 reports results with both a 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 facilitate comparisons, 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 in Panel C. Since coinage issues are attested starting in period 2, $\mathrm{MA}(\mathrm{Coin}_{i,t-1})$ has positive values only starting in period 3. We proceed in two ways: one, we assign values of zero to all cities before period 3, with results reported in columns 1 and 2; two, we restrict the sample to period 3 and later, with results reported in columns 3 and 4. Interestingly, the estimated β does not differ when $\mathrm{MA}(\mathrm{Coin}_{i,t-1})$ is not included in the TWFE model (Panels A and B), but it differs hugely in those two cases with the BJS method (Panel C). When $\mathrm{MA}(\mathrm{Coin}_{i,t-1})$ is included, the estimated coefficient for the adoption of alphabetic writing increases from 0.056 (0.055) to 0.098 (0.093), with the full samples in later periods. This coefficient is always positive and significant, when $\mathrm{MA}(\mathrm{Coin}_{i,t-1})$ is included.

We also try another specification by adding a "pre-period" to the sample during which there was neither alphabetic writing nor coinage issue. With such a "pre-period" we no longer have always treated units. The results are reported in Table 6, columns (5) and (6). Again, the TWFE model (Panels A and B) shows few differences with and without MA($\text{Coin}_{i,t-1}$), but BJS (Panels C) 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 imputed with 250 BCE), and the dates of adoption of alphabetic writing as an independent variable (with censored values imputed with 400 BCE). That is:

$$TimeCoin_i = a_0 + a_1 TimeAlphabetic_i + \mathcal{X}_i \boldsymbol{\beta} + \varepsilon_i. \tag{13}$$

In such a cross-sectional specification, we cannot include the proportion of previous adopters MA($\text{Coin}_{i,t-1}$), but do employ a distance to origin instrument.[46] We evaluate the performance of such an instrument with and without time-invariant spatial controls, centrality, in particular.[47]

[46] "Distance to origin" instruments have been widely used by other studies dealing with diffusion of information. 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.

[47] For regressions in this section, we use, instead of overall market access, authority and hub centralities as defined by Kleinberg (1999) to maximize the utilization of information from the asymmetric directional costs we have. Authority and hub centralities are known to be better measures with directional network (Kleinberg (1999)). These Keinberg centralities are defined in non-matrix form in terms of the elements of

Table 6: Staggered Diff-in-Diff

	Sample: Full		Sample: t>=3		Sample: + Pre	
	(1)	(2)	(3)	(4)	(5)	(6)
	coin	coin	coin	coin	coin	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(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(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 cities 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 alphabetic writing or coinage adoption. But with such a "pre" period we no longer have always treated units. Standard errors clustered at city level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

As mentioned above, a commonly used identification strategy is to use the distance to an appropriate origin as an instrument, and test its validity by "placebo regressions" with distances to other sites. Table 7 reports results with such a procedure for alphabetic writing adoption for the purpose of obtaining a first-stage test with such a distance-based IV. The dependent variable is the date of adoption of alphabetic writing. It is clear that only the distance to origin(s) of alphabetic writing has a strong positive effect, while the distance

$\mathbf{T} = \left[\tau_{ij}^{1-\sigma}\right]$ for $\sigma = 2$, as follows:

$$\mathrm{Au}_i = \sum_j \tau_{ji}^{1-\sigma}\mathrm{Hub}_j; \;\; \mathrm{Hub}_i = \sum_j \tau_{ij}^{1-\sigma}\mathrm{Au}_j. \tag{14}$$

Authority centrality is conceptually akin to the gross value of "inputs" (from "Hubs") by site i ; hub centrality is akin to the gross value of "outputs (to "Authorities") by site i.

Table 7: 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 travels to origins (and other placebo places) on the date of alphabetic writing adoption. It is assumed that all cities adopted alphabetic writing by 400 BCE. Travel times are measured as from city 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-travel*, but results are very similar if we use *To-travel* instead. Standard errors clustered at 1 by 1 degree grid in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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 note though that the distances to origins of alphabetic writing becomes less significant when centrality is included.

We report OLS results in Table 8, columns 1–4. We report results with robust standard errors (in parentheses), and those with standard errors clustered at 1×1 degree grids (in brackets). 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 preceding adoptions, proxied by the respective market access variables. To account for that in the regression reported in column 2 we control for city centrality. In both columns 1 and 2, the date of adoption of alphabetic writing has a positive effect, although at a slightly smaller significance level when clustered standard errors are used (indicated in brackets). In the regressions reported in columns 3 and 4, we additionally control for city size, which causes the date of adoption of alphabetic writing to have smaller coefficients and be less significant. In both the cases with and without size, we note that the date of adoption of alphabetic writing has larger coefficients when centrality is included (reported in columns 2, 4, 6, and 8), consistent with what we saw with the staggered-diff-in-diff regressions.

Columns 5–8, Table 8, report 2SLS results with the distance to potential origins of alphabetic writing as an instrument for date of alphabetic writing 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 7. 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 (13) specifies how adoption of alphabetic writing by a city affects its coinage issue 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.

We conclude that ignoring spatial factors can complicate inference in the estimation of the impact of the adoption of alphabetic writing on coinage issue. 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 alphabetic writing 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 a city's travel network centrality and not using spatially clustered standard errors, can make the distance instrument looks strong and valid while it is actually weak.

Table 8: 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(rb. se)					33.69	20.25	31.40	18.33
F-stat(cl. 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 adoption of alphabetic writing on date of coinage. It is assumed that all cities adopted alphabetic writing 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 origin(s) of alphabetic writing 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5 Conclusions

This paper studies the diffusion of alphabetic writing and coinage across cities in the ancient Mediterranean world. Rather than focusing on the origins of these institutions, the analysis examines how they spread once introduced, documenting common patterns of clustering, path dependence, and propagation along networks of inter-city interaction.

The paper combines a simple diffusion framework with historical evidence to show that adoption patterns for writing and coinage are consistent with exposure-based mechanisms. Cities that were more connected to early adopters were more likely to adopt themselves, even after accounting for local characteristics. These findings do not establish a unique causal mechanism, but they provide evidence that network exposure and strategic complementarities offer a coherent explanation for observed diffusion patterns. Importantly, the analysis does not rely on assumptions about the direction of influence between trade integration and institutional adoption, focusing instead on contemporaneous exposure patterns.

Regarding alphabetic writing, the humanities literature is undecided on where, when and how the Greek alphabet was invented to write the Greek language. Was it in the form of an *Uralphabet* [Astoreca (2021), p. 7], from which the epichoric scripts evolved, or via "local processes of standardisation" [Steele (2021), p. 133]? What exactly happened with the diffusion of the Greek alphabet continues to attract a lot of scholarly attention. Our economic approach aims at elucidating the process by which the adoption of that revolutionary innovation diffused over time in the ancient Greek cities. Regarding alphabetic writing, our findings weigh in favor of Steele (2021) as evidence of direct transmission from potential origins is not confirmed.

As about coinage, it is known that it originated in Sardis. What is not known is exactly how minting of coins diffused in the ancient Greek cities. Coinage is an extraordinary innovation in its own right and enormously significant as a form of money, satisfying its key roles as a store of value, medium of exchange and unit of account. The effect of proximity to previous adopters, other than Sardis, is not important. Sardis appears to have "discouraged" minting of coins in its immediate vicinity. Remote locations are more likely to have monetized earlier. City size dwarfs other factors.

The analysis has several limitations. Historical data on adoption timing are incomplete and measured with uncertainty, and the model abstracts from many institutional and political details that likely mattered in specific contexts. As a result, the paper does not seek to provide a fully structural account of institutional choice or to rank competing explanations for adoption. Instead, it clarifies which classes of diffusion mechanisms are consistent with the historical record and which are not.

The broader contribution of the paper is methodological. By treating institutional change as a diffusion process operating on a network of interacting cities, the analysis illustrates how formal economic frameworks can be used to discipline interpretation in historical settings where sharp identification is infeasible. The results suggest that exposure, complementarities, and coordination problems played an important role in shaping institutional change in the ancient world, and that similar mechanisms may be relevant for understanding the spread of institutions in other historical and contemporary contexts.

The paper does not claim that these mechanisms were unique to the ancient Mediterranean, nor that they operated identically across contexts. As with any historical analysis, the conclusions should be interpreted as suggestive rather than definitive.

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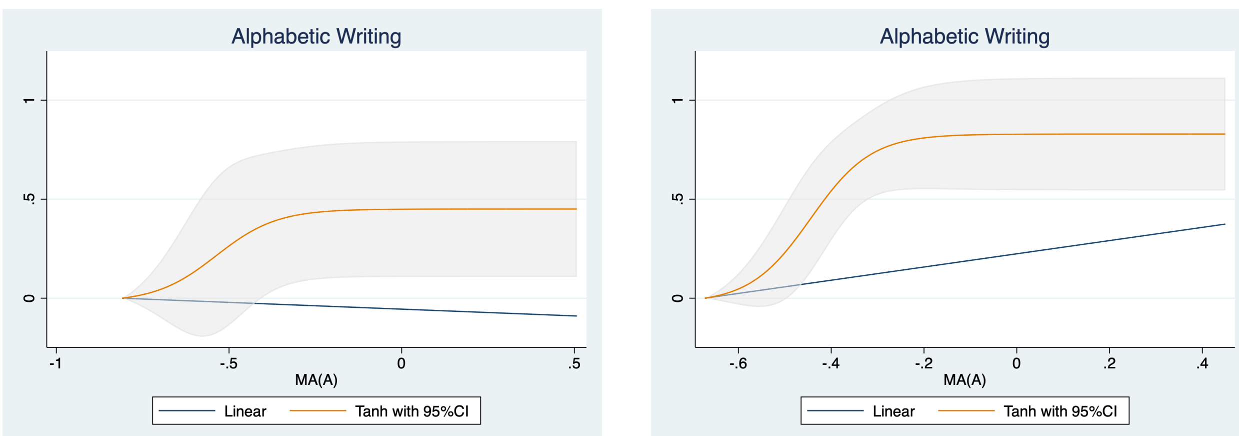
6 Online Appendix: Supplemental Information



(a) To Cost (b) From Cost

Figure A1: Relationship between $\mathrm{MA}(\mathcal{A}_{\nu(i),t-1})$ and adoption in different specifications

Table A1: Spatial Diffusion: the Impact of Proximity to Previous Adopters with Directional Costs

	Linear		Tanh	
	(1)	(2)	(3)	(4)
	Writing	Coin	Writing	Coin
Panel A: To Cost				
MA($A_{i,t-1}$)	-0.137	1.470	-5.692***	-0.0503
	(0.717)	(1.091)	(1.623)	(0.0373)
Constant	-1.423	-0.868	-3.056***	-0.0120
	(0.973)	(0.919)	(0.845)	(0.0314)
a1			-0.471**	-29.25
			(0.200)	(.)
AIC	1335.90	1586.18	1326.52	1586.18
Inflection Pt			-0.54	-0.24
ML Iteration Ct	8	8	71	15000
Panel B: From Cost				
MA($A_{i,t-1}$)	0.667	0.126	-7.673***	-0.0174
	(0.893)	(1.267)	(2.023)	(0.0785)
Constant	-0.758	-1.457	-3.409***	0.0499
	(0.972)	(1.007)	(0.897)	(0.468)
a1			-0.854***	-7.084
			(0.159)	(53.85)
AIC	1328.92	1577.73	1246.35	1579.73
Inflection Pt			-0.44	2.86
ML Iteration Ct	12	6	27	15000
Obs	1151	1499	1151	1499
N(A=1)	410	358	410	358

Notes: Pseudo panel maximum likelihood regressions. The maximum iteration count is set as 15,000 and reaching that number implies convergence is not achieved. Columns (1) and (2) are results for regressions linear in MA($A_{i,t-1}$). Columns (3) and (4) are results for regressions with hyperbolic tangent specification. In all specifications, the linear and squared terms of the MA($A_{i,t-1}$) measured in terms of crow-flies distances are controlled for.

Market access to all cities, 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 alphabetic writing 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Spatial Diffusion: Shapley Decomposition with Directional Costs

	(1) Script	(2) Coin	(3) Script	(4) Coin
Panel A: Regressions using To cost				
MA(adopters) (Travel cost)	18	22	17	7.6
MA(adopters) (crow-flies cost)	28	16	27	5.5
Local geographical variables	38	31	37	9.9
Kleinberg Centrality	9	14	8.8	4.6
Phoenician(Script)/Sardis(Coin)	.9	2.2	.99	.43
Origins(Script)/Mines(Coin)	1.2	6.7	1.1	2
Period FE	5	9.8	4.6	3.8
Size			4.3	66
Panel B: Regressions using From cost				
MA(adopters) (Travel cost)	38	14	36	5.7
MA(adopters) (crow-flies cost)	17	15	16	5.7
Local geographical variables	32	30	32	10
Kleinberg Centrality	4.2	20	3.9	5.4
Phoenician(Script)/Sardis(Coin)	.094	2.6	.11	.45
Origins(Script)/Mines(Coin)	2.8	10	2.9	2.6
Period FE	5	9	4.8	3.9
Size			4	66

Notes: Shapley decomposition of the total regression R2 for the OLS regression with linear, 3rd, and 5th order terms of the travel-cost based MA($A_{i,t-1}$), while all the control variables being the same as in Table 2.