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Ancient coin designs encoded increasing amounts of economic information over centuries

Barbara Pavlek[a,*], James Winters[a], Olivier Morin[a,b]

[a] Max Planck Institute for the Science of Human History, Jena, Germany
[b] Institut Jean Nicod, Département d'études cognitives, ENS, EHESS, PSL University, CNRS, Paris, France

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ABSTRACT

Coinage, the practice of minting small bits of metal with distinctive marks, appearing in the second half of the 7th century BCE, had a transformative impact upon ancient economies and societies. Controversies endure concerning the original function of ancient coinage, in particular the respective role of states and markets in its emergence. Applying information-theoretic measures to a corpus of 6859 distinct coin types from the Ancient Mediterranean world, dated between c. 625 and c. 31 BCE, we show that the symbols minted on coins (designs combining images of plants, deities, animals, etc.) became increasingly informative about a coin's value. This trend was specific to value-relevant information, as distinct from information concerning issuing states. Coin designs also carried more information about higher denominations than about lower ones. Before numerical or written marks of value became widely used on coinage, these iconic symbols were carrying economic information.

1. Introduction

One arresting feature of cultural evolution is information growth (Hidalgo, 2015; Morris, 2013): the capacity of human societies to store and manipulate information has increased by orders of magnitude over the course of human history. Key to this trend is our growing ability to store and manipulate information on economic transactions. Economic transactions can be recorded in two ways. One consists in keeping a trace of the transaction, for instance as an IOU, or as an inscription in a register. The second solution consists in exchanging tokens of value, such as coins. In the latter case, no record of the transaction needs to be produced or kept: one agent simply gains tokens of value that used to belong to another agent. In this way, the distribution of tokens of value among agents in a market can record vital economic information, in a decentralized way (Hayek, 1945), thus lowering transaction costs (Bresson, 2009).

Things that can serve as exchangeable tokens of value exist in many cultures and can take many forms: from cows and cowrie shells to silver coins and paper money (Dalton, 1965). What some chartalist economists call a "money-thing" is an object that embodies the abstract concept of "money" and functions as a means of exchange (Wray, 2012, p. 43). Coins are often recognized as the first "money-thing" which successfully combined the three functions of money, serving simultaneously as unit of account, means of exchange, and store of value (Bresson, 2006; Peacock, 2006; Schaps, 2004, p. 15; Seaford, 2004, pp. 16–19; but see: Van Alfen, 2018). Coins are but one kind of money-thing: discs of precious metal stamped with distinctive graphical symbols. These symbols set coins apart from other money-things such as unminted bullion, cows, or ingots, and they clearly played a defining role in the emergence of coined money. Yet the exact meaning of the images found on early coinage remains an open question. What did they refer to? The debates over this question tend to follow the lines of a long-standing controversy over the respective role of states and markets in the appearance of early coins. Coins may be seen either as representations of a state's debt toward anyone who carried its coins (Knapp, 1905; Ingham, 2004; Schaps, 2004; Seaford, 2004; Wray, 2012, pp. 148–186), or as tools to facilitate market transactions (Menger, 1892; Bresson, 2006). These discussions do not only influence our outlook on ancient coins. They bear upon the very nature of money, with wide-ranging implications concerning which functions money, coined or not, would best fulfil (Graeber, 2011). If (to simplify matters a good deal) a coin is taken to represent an IOU issued by a state, divorced from any other type of value, this reinforces a view of monetised economies as political innovations alien to traditional exchange systems (Bohannan, 1955; Polanyi, 1944). If, on the other hand, coins stand for units of value whose utility derives in large part from decentralised market exchanges that may exist independently of state authorities, this authorises a view of monetary exchanges as in some ways continuous

* Corresponding author at: Max Planck Institute for the Science of Human History, 10, Kahlaische Strasse, 07745 Jena, Germany.
E-mail address: pavlek@shh.mpg.de (B. Pavlek).

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with non-monetary ones (Menger, 1892). These issues have been at the heart of economic anthropology since the debate between formalists and substantivists in the second half of the twentieth century (Dalton, 1965; Firth, 1972; Hejeebu and McCloskey, 1999; Polanyi, 1944). Without hoping to settle these debates here, we think that a good way to figure out what coined money stood for is to explore the meaning of coin designs, the key innovation that turned bits of metal into coins.

Many types of money-things existed before and after coinage was invented in the 7th century BCE on the coast of Asia Minor (de Callataÿ, 2013; Howgego, 1995, pp. 1–3; Kraay, 1976, p. 24 ff.; Wallace, 1987). Gold or silver had been used as money-things long before coins, and later continued to circulate as bullion or ingots (Kroll, 2008; von Reden, 1997). Compared to most other types of money-things, precious metals are appreciably durable and transportable; but they have one drawback. Dividing a lump of gold or silver into small, precise, standardized quantities is costly. This cost escalates as the quantity to be divided gets smaller (Bresson, 2006; Sargent and Velde, 2003). This made precious metal inconvenient to use for anything but exceptionally important transactions. Coins can be seen as a partial solution to this problem, although they do not seem to have been invented for that purpose. They first developed in Lydia (an Anatolian kingdom) as a way to deal with the high variability of electrum, an alloy of silver and gold (Schaps, 2004, pp. 96–101; Wallace, 1987). Striking bits of electrum into coins allowed private or state mints to guarantee the coins' recipients against fraud, by promising that the coin's issuer, identified by their seal mark, would buy the coin back. Coins from the royal Lydian mints were more valuable than both unmarked bits of electrum and other coins, because the Lydian minters had found ways to stabilize the gold/silver ratio of their coins (Melitz, 2017), and because the state's promise to redeem the coins it issued was more credible than any private party's guarantee, given the state's permanence and power (Ingham, 2004; Seaford, 2004, pp. 134–135; Wray, 2012, pp. 148–186). This allowed the state to extract a seigniorage premium from the coins it issued. In addition to possible direct profits to Lydian rulers, this premium also made the expensive minting of low-denomination coins affordable (Melitz, 2017). Investing in small change could benefit the state by lowering its own transaction costs when collecting or issuing economic transfers (Sugden, 1992; Van Alfen, 2012), and by stimulating trade (Seaford, 2004, pp. 135–136).

From c. 550 BCE on, Greek city-states started minting silver coins in large numbers. As with electrum, minting silver allowed Greek city-states to extract a premium, part of which could be invested in the minting of low denomination coins. Precious metal was made available to anyone in standardized quantities, reducing transaction costs both for traders and for the city-state's own administration (Melitz, 2017; Sugden, 1992). These coins were the first object that could be used to store value, settle transactions, and keep accounts, across a wide range of domains, from everyday purchases to judiciary settlements, war, and politics – making coins the first universal and impersonal "money-thing" (Seaford, 2004, pp. 152–157; Schaps, 2004, pp. 31; 194 ff.).

2. Information in coin designs

We are using the term "coin designs" to describe a unique combination of images composed of motifs imprinted on both sides of a coin (obverse and reverse). What we call a "coin type" is a set of coins of a certain denomination sharing the same design, issued by the same authority in the same period (as opposed to "coin tokens" which would refer to individual exemplars of a coin type). Our use of this term differs from its usual use in numismatics, where a "type" is the central motif struck by a die on either side of a coin: by the obverse die, embedded in the anvil, or by the reverse die, engraved in a hand-held punch. The differences between the obverse and the reverse side of an ancient coin are primarily technical, in that the design on the obverse side is usually convex, whereas the one on the reverse side is slightly concave or incuse (Metcalf, 2012). At first, coin designs were simple impressions made on a coin's surface ("incuse marks"), but soon they started to include figurative motifs chosen from the existing graphic repertoire inspired mainly by mythology, but also local geography, animals, plants or famous local products. Some of these motifs could also be found on seals or as state emblems (Kraay, 1976, pp. 3–4; Wallace, 1987; Spier, 1990; Killen, 2017). On the earliest coins, the graphic design was featured only on one side, usually the one struck from the obverse die, whereas the reverse included only a punch mark, before the adoption of figurative motifs, which frequently complemented the iconography of the obverse (Head, 1911, p. lvi ff.; Kraay, 1976, pp. 2–5; Carradice and Price, 1988, pp. 56–61). Although the obverse side usually bears the main motif (often a portrait head), this is not always the case (Kraay, 1976, p. 17).

Most coins of the ancient Mediterranean did not carry any numerical or written indication about their value. The base metal coins that first appeared in Sicily and southern Italy in the 5th century BCE contained such indications, but they were a small minority (Kraay, 1976, pp. 7-8; Rutter, 1983, p. 30).

What was the meaning of coin designs? Ancient Greek sources saw coins as a mean to certify the quality and value of a piece of silver, obviating the need for costly weighing or assaying operations (Bresson, 2006; Schaps, 2004, p. 195 ff.; Seaford, 2004, p. 127). The fact that fine silver coins such as Athens' tetradrachms circulated far outside their issuing city-state illustrates their intrinsic metal value (Howgego, 1995, pp. 92–93). Greek silver was purer than electrum, so the value of a Greek silver coin was clearly (though not perfectly) indicated by its size and weight (Velde, 2014). There are indications that these coins were valued over and above their sheer metal weight (Seaford, 2004, pp. 136–146). The circulation of base metal coins, from the late 5th century on, also demonstrates that coinage could possess a fiduciary value beyond its metal content (Carradice and Price, 1988, pp. 99–102; Rutter, 1983; Seaford, 2004, pp. 137–139). Coins, thus, seem to have indicated both information about their denomination – the value of a coin relative to that of other coins, usually proportional to its silver weight –, and information concerning their issuing authority, usually the city-state that minted them.

We aim to predict and measure the amount of state- and value-relevant information in ancient coin designs. We see coin designs as a culturally evolved graphic code (Morin et al., 2018). Modern coin designs (with rare exceptions) are almost perfectly informative: they tell us everything we need to know about a coin's denomination and issuing authority, without having to verify the coin's value or provenance (occasional forged coins notwithstanding). Such perfectly informative designs took time to evolve: ancient coin designs were not optimally informative.

Authenticating a coin's issuing authority was, we assume, a design's foremost function. A coin's value could be deduced from its size and weight; its issuer could not. We therefore expect the designs initially to carry high amounts of state-relevant information. With time, however, we expect state-relevant information to decrease due to the effects of cultural transmission. Artefacts or labels that serve to identify persons or institutions – things like names, flags, or heraldic emblems – become less distinctive when imitated. Data concerning the diffusion of medieval European heraldic symbols show that high-fidelity copying can make visual symbols less informative, when two distinct agents copy the symbol that is supposed to identify them (Morin and Miton, 2018). Ancient coin designs were a different form of graphic identifier, but we assumed that the gradual cultural and political integration of the Greek world, from individual poleis to large Hellenistic kingdoms, facilitated the diffusion of coin designs among mints, thus reducing the amount of information the coin designs carry about their issuing authority. The political consolidation of the Ancient Greek world – through colonization, alliances, federations, and, lastly, Alexander the Great's conquests – enabled the formation of monetary unions, whose members minted coins with similar or identical designs as a way to signal allegiance (Economou et al., 2015; Howgego, 1995, p. 63; Mackil and Van Alfen, 2006). An authority's coin designs may also have been copied for economic gain, for instance when a debased currency imitated a stronger one (Spufford, 1988; Van Alfen, 2005). Alternatively, the designs could travel between city-states with skilled artists and minters employed to produce coins for several neighbouring cities (de Callataÿ, 2012; Carradice and Price, 1988, p. 63).

Contrary to information about authorities, information about value is less crucial to signal, since it can be approximately recovered from a coin's size and weight. This would predict initially low levels of value-relevant information in coin designs. The dynamics of ancient economic history, however, should have prompted it to grow. The world where coinage evolved was one of spectacular economic growth and ever-increasing market integration (Ober, 2015; Osborne, 2009). Even then, the coinage of most city-states never circulated far from its place of origin (Carradice and Price, 1988, p. 90; Kraay, 1964). Monetized trade between cities was often hindered by a multitude of coexisting weight standards, deepened by differing policies on silver content management and regulations forcing holders of foreign currencies to exchange them at unfavourable rates for local coinage. In spite of this, economically powerful city-states (like Athens, Corinth and Aegina) managed to maintain a consistent quality and weight for their silver coins, which became reputable enough to be widely accepted as a means of exchange (Howgego, 1995, pp. 95-98).

Frequent economic exchange across different city-states would have made it practical for coins to be exchangeable at their face value, without requiring to weigh them (Bresson, 2009). It was common for smaller city-states to align on the weight standard of their more prosperous neighbours, like the Attic/Euboïc standard used in Athens. This lowered transaction costs and encouraged trade between cities (Bresson, 2006; Psoma, 2015; Van Alfen, 2005). Using identical designs for identical denominations makes sense in this context. A design that is adopted by different states becomes less state-distinctive (being shared by several distinct authorities), but not necessarily less value-distinctive. To the extent that the designs minted on coins make coins issued by different authorities more distinctive, we shall say that they carry *state-relevant information*. If the designs highlight the distinct values of different coins, they carry *value-relevant information*. State- and value-relevant information can both increase or decrease in parallel, but they may also evolve in different directions. In the case at hand, we predicted that economic and cultural integration should weaken state-relevant information, but strengthen value-relevant information.

Our general hypothesis is that the amount of information carried by ancient designs evolved in response to specific functional pressures. We pre-registered three hypotheses. Initially, the amount of state-relevant information carried by coin designs was high, but it decreased with time due to the cultural diffusion of designs across city-states. As trade between states increased in prominence, value-relevant information became increasingly indispensable, resulting in its growth. Lastly, we reasoned that minters signalled the coins' values more carefully for small coins, as a way to advertise their skill at producing reliable low denominations. Lower denominations are more sensitive to imprecision from weighing errors: a margin of error of one milligram of silver would have almost no impact on a sum of silver minted in high denominations, but a much bigger impact on the same amount, if denominated in smaller change (Bresson, 2006; Melitz, 2017). In order to compensate for this, the value of low-denomination coins should be specifically advertised. Therefore, we predicted that value-relevant information would in general be higher for low-value coins.

3. Measuring information

Conditional entropy (Shannon, 1948; Sproat and Hall, 2014) allows us to quantify the precision of the mapping between coin designs and coin characteristics: here, an inverse relationship exists, whereby higher entropy corresponds to a less informative mapping. Consider a set of coins issued by a variety of states. If seeing all the designs on all the coins is enough to determine with certainty which state issued which coins, the conditional entropy of states given coin designs is zero, and thus the state-relevant information carried by designs is optimally high. If knowing the designs is not enough to attribute every coin to its state, this increases the relevant conditional entropy, lowering the amount of information carried by the designs (Fig. 1). Conditional entropy is sensitive to baseline changes in the entropy of the main variable (states, in our example). To control for this, we normalize the conditional entropy using basic entropy as the normalizing constant.

All our measures of information were calculated over subsets of coin types, using conditional entropy or normalized conditional entropy. The conditional entropy of A given B (Shannon, 1948) is given by equation (1):

$$H(A|B) = -\sum_{b\in B} P(b) \sum_{a\in A} P(a|b)\log P(a|b) \quad (1)$$

where $H(A|B)$ is the conditional entropy of A given B, both A and B being sets of categories. Depending on the measure at hand, A or B can stand for sets of authorities, denominations, or designs. If, for instance, we are calculating the state-relevant information carried by designs, over a given subset of coins, what we want to compute is H(authorities | designs). In that case, A is the set of all authorities represented in the subset (e.g., “Corinth”, “Athens”, etc.), and B the corresponding set of designs (e.g., “Dolphin + Crown”, “Athena + Owl”, etc.), $a \in A$ and $b \in B$ being individual authorities or designs. P(b) is the frequency of individual design b, while $P(a|b)$ is the probability that coins with design b are issued by authority a. Entropy is measured in nats, units based on natural logarithms (base e).

The conditional entropy of A given B is crucially influenced by the entropy of A, which has to be controlled for. To this end, we computed normalized conditional entropy, $H(A|B)/H(A)$, where $H(A|B)$ is given by equation (1), H(A) by equation (2):

$$H(A) = \sum_{a\in A} P(a)\log P(a) \quad (2)$$

The functions ‘entropy’ and ‘condentropy’ of the *infotheo* package (Meyer, 2014) for R (R Core Team, 2017) were used for all such calculations. Our code and data are fully available (see Code and data availability).

4. Dataset

We used a corpus of 6859 types of coins (“coins” for short), each being characterized by a unique combination of the images on the obverse and reverse side of a coin (“design”), denomination, issuing authority, and date. The corpus represents the broad reach of coinage practices in the Mediterranean, heavily influenced by the city-states of mainland Greece (Howgego, 1995, pp. 1–2). In addition to the coinage of Greek city-states and colonies all over the Mediterranean, our corpus also includes the coinage of other ancient Mediterranean civilizations (Parthian, Jewish Hellenistic, Celtic), and the coinage of the Hellenistic states born of Alexander’s conquests. We collected the data from two online databases, the Sylloge Nummorum Graecorum (SNG) project of the British Academy (Carradice and Popescu, n.d.) and the “MANTIS” online database of the American Numismatic Society (American Numismatic Society, 2015).

Our analysis focused on the period c. 625 BCE – 31 BCE, from the invention of coinage to the Roman victory at Actium.[1] The corpus was

[1] The study presented here builds upon two preliminary studies that were carried on two distinct datasets, one based on the SNG data (1548 coin types c. 650 – c. 336 BCE), and the other based on MANTIS data (5375 coin types, c. 580 – c. 31 BCE), each testing slightly different predictions. For the main study, reported here, we pooled together the two datasets, and re-tested all the predictions from both studies. Both preliminary studies were preregistered, and their complete results are reported in the Electronic Supplementary Material.

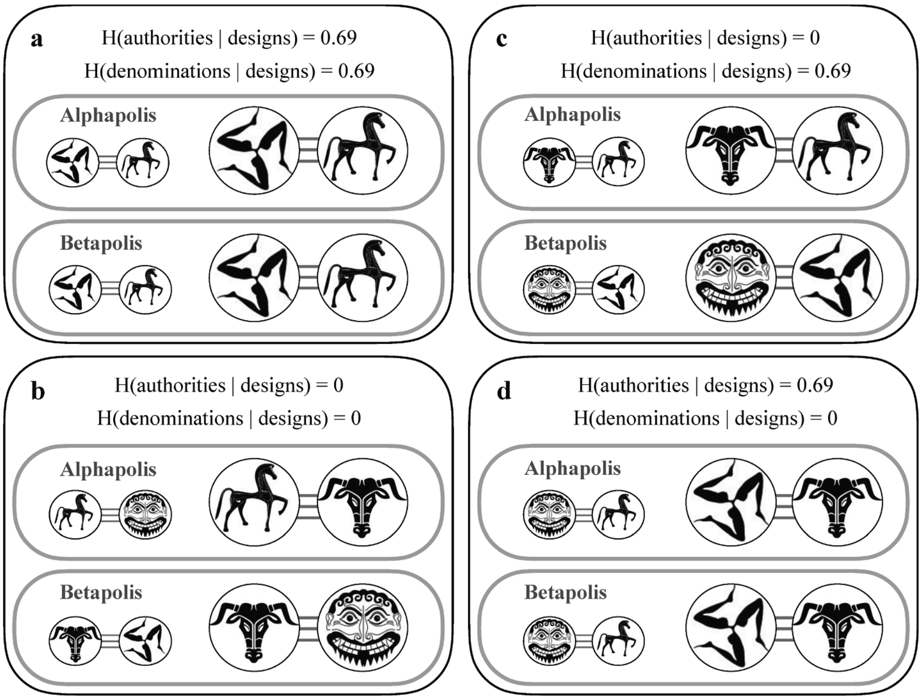

Fig. 1. Conditional entropy measures the amount of information that coin designs carry about their issuing authority or denomination. Two city-states, Alphapolis and Betapolis, issue two different coins, one for each denomination: the "small coin" and the "large coin". When all four coin designs are identical **(a)**, they carry no information about a coin's city-state or denomination. The conditional entropy (given in nats, see formula **1**) of authorities given designs is the same as the conditional entropy of denominations given designs, 0.69 nats (natural logarithm of 2). **(b)** In an optimally efficient system, each coin carries a different design, and both conditional entropies are equal to zero. **(c)** If each city-state issues the same design for each denomination, but the coins of each city-state differ, designs are optimally informative about authorities (conditional entropy of zero), but carry no information about denominations. **(d)** Conversely, if both city-states use the same two distinct designs for each denomination, designs are optimally informative about denominations (as opposed to authorities).

constituted by selecting the coins dated to the relevant time period, whose entries included information on issuing authority and denomination, and the descriptions of the images on the obverse and reverse side. To determine each coin's issuing authority, we combined the information given by the databases in the following way: the information concerning the state authority issuing the coins (e.g., Corinth, Athens, Alexander III) was prioritized, but if missing, it was replaced by information on the mint. In case both state and mint were missing, we used the coin's geographical provenance (region). We used the coins' denominations as given by our sources (ancient denominations were fairly homogeneous and are well documented).

The databases provided us with a detailed description of the images found on the obverse and reverse sides of a coin. However, these descriptions are often subjective and idiosyncratic. We were therefore faced with the task of identifying the individual motifs, normalizing the motif names, and creating standardized coin design descriptions in order to be able to identify unique coin types. We made a list of all the motifs found on each coin in the database, focusing on individual human figures, animals, plants, objects, and symbols, and excluding inscriptions (monograms, personal or place names). We disregarded the motifs that rarely appear independently and were either more likely to appear as attributes of a particular character (e.g. Herakles' lion skin), or as part of the character's clothing. Variants of the same motif (different kinds of helmets, stars, etc.) were treated as simple instances of the basic motif. Similarly, we took into account only one occurrence of a motif on a coin, irrespective of how many times that motif appears on that coin. Orthographic and terminological variants were standardized. Finally, we merged all the motifs on a given coin into a single alphabetically arranged string, which we treated as the coin's design.

In both online databases used as data sources, the coins' dates were given as time intervals of varying width. For each coin, this interval was constrained to a single year (the median year in the interval). Since our conditional entropy measures need to be calculated over data bins of roughly homogeneous sizes, we used an unsupervised discretization algorithm (the "discretize" function of the *infotheo* package in R) to divide the corpus into 18 chronological windows or "date bins", each corresponding to a time interval, and containing an approximately equal number of coins (see Electronic Supplementary Material, section 0.4). The "date bins" were assigned chronological labels, representing the number of years between the median year of the earliest period until the median year of the period in question. Whenever several coins shared the same date(s), authority, denomination and design, we discarded every coin but one. Thus, our data contains not individual coins (tokens), but coin types, sharing the same design, authority, and denomination.

In order to test our last prediction, the coins had to be binned into subsets according to their denomination ("high" or "low"). Based on standard numismatic references (Head, 1911; Kraay, 1976), we determined the "base value" of each coin. For instance, the base value for a 2 euros coin would be 1 euro, as it would be for a 50 euro cents. Based on each coin's weight standard value, we calculated the coin's value in relation to this base value (see Electronic Supplementary Material, section 0.4). All coins above this base value were deemed high-value coins, all coins below were treated as low-values. Coins exactly at base value were ignored when testing this prediction. There typically were more denominations above the base value than below. This bias is corrected for when normalized conditional entropy is used.

5. Results

When testing the chronological predictions, the coin types were arranged by approximate date, into 18 "date bins", each dated by their median year (here called "DATE"). For each date bin, we calculated the coin designs' state-relevant information, as indexed by the conditional entropy of authorities given designs, and their value-relevant information, as indexed by the conditional entropy of denominations given designs. The predictions were tested by nested regressions performed using *lmerTest* (Kuznetsova et al., 2017) in R. All p-values reported in this paper are two-tailed.

We found a significant drop in state-relevant information with time: the conditional entropy of authorities given designs becomes higher with time, corresponding to a decrease in informational value (Spearman's $\rho = 0.529$, $p = 0.026$). The same trend obtains if we measure information by normalized conditional entropy (Spearman's $\rho = 0.566$, $p = 0.016$). This trend is, however, almost entirely driven by one event: the amount of state-relevant information present on coins dropped spectacularly in the period surrounding the death of Alexander the Great (323 BCE) (Fig. 2) The rise of Macedon, starting with Philip II's victory in the Battle of Chaeronea in 338 BCE and continuing with

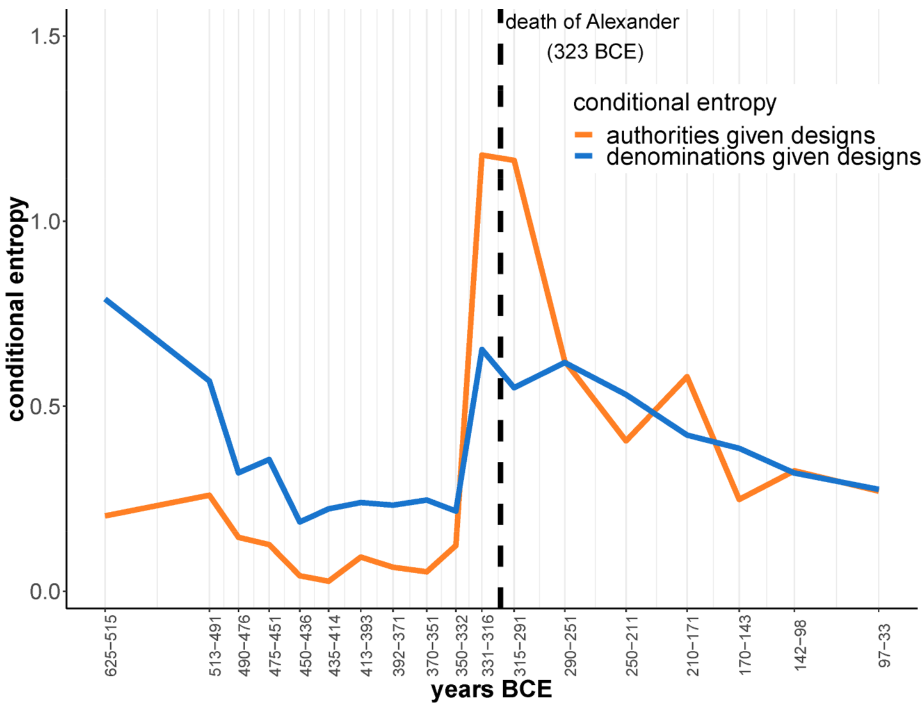

Fig. 2. The evolution of state-relevant information and value-relevant information in ancient Greek coins (c. 625–c.33 BCE). The state-relevant information carried by coin designs (orange line) is indicated by the conditional entropy of the coins' issuing authorities given their designs, and value-relevant information (blue line) by the conditional entropy of the coins' denominations given their designs. Conditional entropy values are given in nats, on the y-axis. High entropy indicates low information. The values were computed over 18 "time bins", obtained by dividing our corpus of 6859 coin types according to their dates, with an unsupervised discretization algorithm, into bins containing approximately equal number of coins ($289 < n < 501$, see Table 7 of the Electronic Supplementary Materials for complete information on bin sizes). The time bins are indicated on the x-axis as time intervals BCE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Alexander's conquests until his death in 323 BCE, resulted in the creation of a unified, but short-lived, Hellenistic state. Alexander the Great issued coins with standardized designs in numerous mints across his great empire, thus forming a monetary zone of an unprecedented scale. Of good quality and minted on a single weight standard, the coinage from Alexander's mints was produced in large quantities and widely accepted, replacing most local city-state coinage (Carradice and Price, 1988, p. 104 ff.; Howgego, 1995, p. 48 ff.; Rutter, 1983, p. 36 ff.). In that new context of a single dominating authority, signalling the provenance of coins became less relevant. The royal mints endured after Alexander: Hellenistic kings minted coinage with images borrowed from Alexander, as a posthumous tribute to their predecessor, and as a way to legitimize their own power (Meadows, 2014; Carradice and Price, 1988, p. 115 ff.; Howgego, 1995, p. 51 ff.). Later, when successors started issuing coinage with their own designs, the diversity of designs increased, and they again became informative as state symbols in the politically fragmented Hellenistic world.

As most of the authorities in our dataset produced several distinct denominations, the coins for each of the 18 time-bins have been split according to their issuing authority, to avoid giving undue importance to the minority of authorities that issued many coin types. Without this control, value-relevant information does not appear to rise (Spearman's $\rho = 0.036$, $p = 0.888$), but it does if we consider the average amount of value-relevant information on the coins of distinct authorities (Fig. 3). To show this, we performed two nested regressions using, as data points, the value-relevant information carried by the coins issued by a particular authority in one time-bin, for instance Corinth (413–393), Corinth (315–291), or Athens (315–291). In the first analysis, value-relevant information was computed as the conditional entropy of denominations given designs. We first ran a null model nesting each data point by the relevant authority (e.g., Corinth, Athens). We compared this null model with a model using the median year of each time bin (its DATE) as predictor. That model had a lower AIC than the null model ($AIC_{null} = 485$ vs. $AIC_{test} = 472$) and included a negative estimate for the effect of DATE ($\beta = -0.0002$; $SE = 0.0001$; $t = -3.942$; $p < 0.0001$). This result held when we used normalized conditional entropy instead of conditional entropy as our measure of information ($AIC_{null} = 496$ vs. $AIC_{test} = 493$, estimate for the effect of DATE: $\beta = -0.0002$; $SE = 0.0001$; $t = -2.292$; $p = 0.0223$). Once again, Alexander's rise was accompanied by a weakening of the amount of information carried by coin designs, most likely due to the indiscriminate use of a few very frequent designs on the coins of distinct denominations, thus confusing them. However, the decrease is temporary, and value-relevant information grows again in later periods.

Two candidate mechanisms can explain the increase in value-relevant information. (1) Coin designs might have been used more consistently with time, with different minters using the same design for the same denomination. (2) Coin designs might simply have diversified: a greater number of unique designs would be created, with no rationalization in their use. The first possibility can be tested by considering the conditional entropy of designs given denominations —which measures to what extent one can predict which designs will figure on a coin just by knowing its denomination. If hypothesis (1) is true, and designs were used in an increasingly consistent way, then the conditional entropy of designs given denominations should decrease over time. Looking at simple time bins, not subdivided by authorities, we do not see a clear trend in that direction (Spearman's $\rho = -0.218$, $p = 0.384$). If we keep coins from different authorities distinct, and perform a nested regression, comparing (as previously) a null model where each data point (one coin type in one time-bin) is nested according to its authority, with a model that adds DATE as predictor, the DATE model is more informative ($AIC_{null} = 2375.3$ vs. $AIC_{test} = 2374.9$). It also includes a negative estimate for the effect of DATE ($\beta = -0.0001$; $SE = 0.0001$; $t = -1.558$; $p = 0.12$). This trend, however, is too small to explain most of the increase in value-relevant information. This analysis cannot directly confirm that the rise of value-relevant information was primarily caused by a more consistent use of coin designs. However, we observe a tendency for most authorities to reduce the number of designs used on their coins (see Electronic Supplementary Material, Fig. 12). The most famous example is Athens, which shifted from a coinage intended for internal use, marked by a variety of different designs (the so-called *Wappenmünzen*), to a coinage characterized by a single design that included the famous Athenian owl, which became successful in the inter-city trade (Kroll, 1981; Schaps, 2004, p. 105). This general reduction in design diversity did not prevent the steady increase of the amount of value-relevant information.

Value-relevant information, we predicted, should be higher for low denominations. We found the opposite result (see Fig. 4). Having

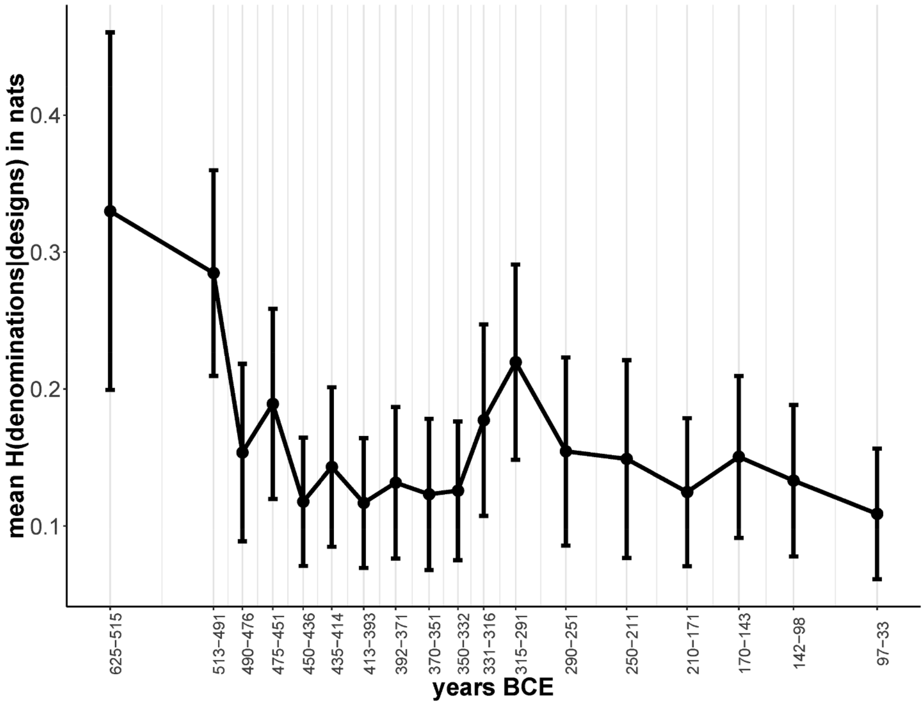

Fig. 3. The evolution of the value-relevant information carried by ancient Greek coins, on average, across distinct states (c. 625–c.33 BCE). Value-relevant information was computed as the conditional entropy of denominations given designs (in nats), on the y-axis. High entropy indicates low information. Each time bin is indicated on the x-axis as a time interval BCE. Each time bin was further split into sub-bins, according to the coins' issuing authorities (total n = 601 distinct authorities). Conditional entropy was computed over each of these sub-bins (total n = 1476). Each data point indicates the average amount of value-relevant information carried by coins of the distinct authorities represented in the dataset for that period. Error bars = 95% confidence intervals.

divided our corpus into two subsets, high- and low-value coins, we subdivided each subset into authority-specific bins: e.g. low Corinthian denominations, high Athenian denominations, etc. For each subset, we calculated the designs' value-relevant information, as given by the conditional entropy of denominations given designs. Nested regression was not suitable to test this prediction, because of the structure of the data: the variance of the nesting variable could not be estimated due to the scarcity of different data points per nesting variable. The effect of "high" vs. "low" values was therefore tested using a Wilcoxon rank sum test. Contrary to our predictions, coin designs on high-value coins carried *more* value-relevant information than designs on low-value coins ($W = 18{,}667$; $p < 0.0001$). Using normalized conditional entropy (dividing the conditional entropy of denominations given designs by the entropy of denominations) did not change this effect ($W = 19{,}748$; $p < 0.0001$).

This result could be due to the fact that high-value coins, being larger, can fit more complex and diverse designs (even though motifs can be, and often were, miniaturized). To verify this, we grouped our coin types according to the number of motifs contained in their design. We calculated the designs' value-relevant information for each subset (for instance, 1-motif low-value coins, 2-motifs high-value coins, etc.). This analysis confirmed our initial result for simple conditional entropy ($W = 17.5$; $p = 0.0033$) as well as normalized conditional entropy ($W = 30.5$; $p = 0.0334$) (Fig. 4.). We can therefore rule out the possibility that high-value coins contain more value-relevant information because they bear a larger number of motifs.

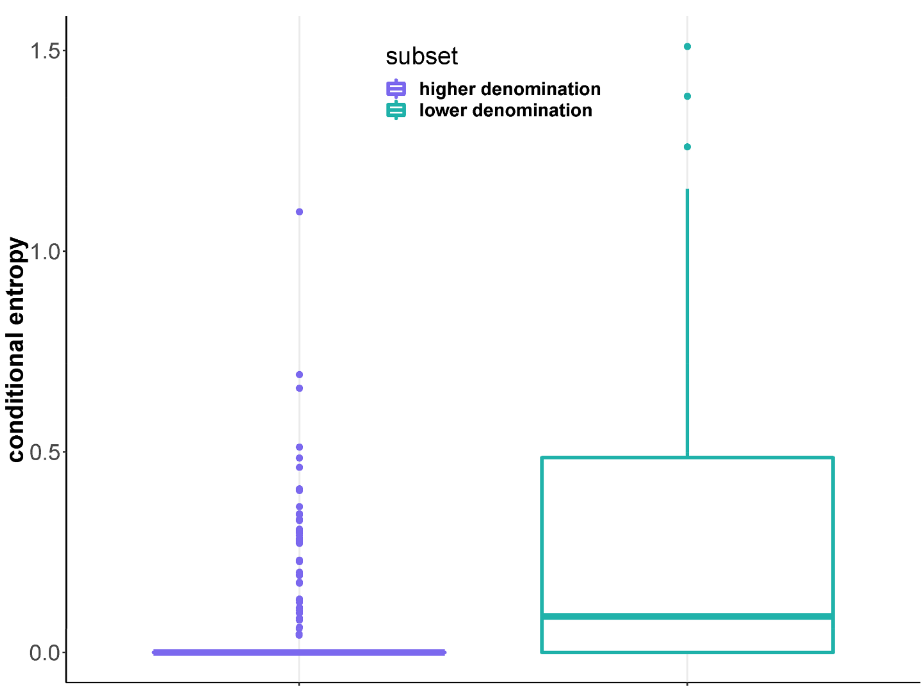

Fig. 4. The value-relevant information carried by the designs of the low-value and high-value coins issued by 353 authorities. Value-relevant information was measured as the conditional entropy of the coins' denominations given their designs (on the y-axis, in nats). High-denomination coin types (in purple, total n = 2485) are compared with low-denomination coin types (in green, total n = 1966). Inside each category, coins were binned according to their issuing authorities (247 authorities for high-value coins, 241 authorities for low-value coins). Conditional entropy was computed separately on each individual bin. Boxes: 2d to 3d quartiles, lines: median values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions

Having perfectly informative coin designs, explicitly signalling the coin's denomination and issuing authority, is the norm in modern societies. Yet this solution had to be discovered gradually by cultural evolutionary processes. Ancient coins were consistently highly informative about their issuing authority in the first two centuries of their evolution, consistent with theories claiming an important fiduciary aspect for early coinage (Seaford, 2004, pp. 136–146; Wray, 2012, pp. 148–186). However, political integration in combination with cultural transmission in the second half of the 4th century BCE eroded the coins' capacity to carry information about the issuing state. The coinage with a limited number of standardized designs produced in the name of Alexander the Great dominated over the local city-state coinage and degraded the distinctiveness of coined money in the Hellenic world during Alexander's rule, and in the short period after his death. After this disruption, we can again observe an increase in state-relevant information similar to the one preceding the rise of Macedon. Value-relevant information followed the opposite trend: weak at first, becoming stronger. The rise of value-relevant information would have been even more visible had we taken into account the written and numerical marks that started to appear on bronze coins in the late 5th c. BCE (Kraay, 1976, pp. 7-8; Rutter, 1983, p. 30) — but only symbolic imagery was considered. Our findings do not settle the long-standing debate on the origins of coined money, but they do provide new evidence for two relevant facts. Coin designs initially carried more information about the state that minted them than about their value, consistent with the view that state symbolism was central to early coinage (Seaford, 2004). On the other hand, the same designs did carry economic information, a quantity that increased with the political and economic integration of the Ancient Mediterranean world.

The signalling of denominations was not indiscriminate: it favoured higher denominations, not lower ones, perhaps because greater value differentials in the high-denominations range made these coins more valuable to signal. Coinage, today as in ancient times, has a non-linear denominational structure: gaps between denominations become disproportionately larger as denominations grow. The value differential between one euro cent and two euro cents is one hundred times smaller than that between one euro and two euros. The cost of mistaking one denomination for another rises correspondingly, justifying that minters signal higher denominations with more distinctive designs. If this last conjecture is true, we should find that the distinctiveness of coins increases proportionally with the value gaps between denominations, in modern monetary systems as well as ancient ones. If confirmed, this would provide evidence for a phenomenon well known to cognitive linguistics: symbols face a trade-off between simplicity and informativeness, which can be solved by taking into account the users' communicative needs, using more informative symbols for more relevant items (Regier et al., 2015). For instance, colour vocabularies across cultures are more precise for colours that are more frequently referred to (e.g., the various shades of red vs. the various shades of blue). This hypothesis had so far only been tested on data from natural languages (Gibson et al., 2017; Kemp and Regier, 2012; Regier et al., 2015) or experimentally generated ones (Carr et al., 2018). Our data suggest that it could be extended to graphic symbols such as coin designs.

This study adds plausibility to the view that the earliest coins did carry state symbols (a view put forward on the basis of similarity with contemporary images found on official seals, weights or public monuments: Wallace, 1987; Spier, 1990; Killen, 2017). The fact that designs carried value-relevant information is more surprising, since written or numerical denominational marks were very rare on Greek coinage (Kraay, 1976, pp. 7-8; Rutter, 1983, p. 30). Outside of written or numerical signs, some symbols have been mooted as having possible value-relevant meaning: incuse marks on early electrum coins (Velde, 2014), the number of horses on Syracuse's chariot emblem, or variations on Corinth's winged horse (Kraay, 1976, p. 4). Yet none of these is uncontroversial. Our study confirms that early coin designs did carry value-relevant information.

The recording of transactions is one of the most important tasks that symbols were put to: it was central to the evolution of numeration symbols, writing systems, and coinage (Wang, 2014). Ancient seals, an important source of early coinage imagery (Seaford, 2004, pp. 115–124; Wallace, 1987), carried two basic kinds of information. They could carry information about the content of a sealed package of goods, a function that became increasingly important in the context of the early evolution of writing (Schmandt-Besserat, 1996). They could also identify an individual or an institution, as an owner of goods or as the author of a document. Coinage marks did not continue these precise two functions, but repurposed them in innovative ways. Coin designs worked as emblems for the state that minted them, although cross-state cultural exchanges made them less informative with time, as shown by the imagery linked to Alexander's reign. Coin designs also came increasingly to reflect the amount of currency they stood for, in a way that was sensitive to the denominations' values. Later monetary systems would complete the trend, with the systematic use of explicit marks of value that ancient Greeks used only for base metal coins. Such marks of value appear again in the form of monograms on Roman and Byzantine coinage, and later more or less consistently since the 17th century (Kluge, 2016, pp. 12–13). Solving the seemingly mundane problem of optimally signalling a coin's value took several centuries of cultural evolution.

Code and data availability

Our code and data are available at http://osf.io/tkv67/?view_only=65bc6dbcc69c49308491598a95f15c6b.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaa.2019.101103.

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