The Cultural Evolution of Coinage as an Informational System

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by

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1. Introduction

1.1. General scope: numismatics and archaeology

Coins are peculiar items of human material culture. They can be defined as physical representations of monetary value, used primarily as media of exchange. Although they have been around for centuries, and come in many shapes and sizes, their general appearance has remained constant: they are usually small, round, two-sided metal pieces marked with inscriptions, often accompanied by a graphic design. This stability helped establish coins as the most common type of monetary objects, recognized by their users as a valid means of payment (Cribb, 2009, p. 426). However, political and economic circumstances as well as techniques of coin production and use have changed through history, from the first coins made of weighed precious metal, to the modern fiduciary token coins, whose value is no longer intrinsic, based on their metal content, but established and regulated by monetary authorities. These changes have influenced the way coins were made through history, and the respective importance of their various properties, such as weight, size, colour, text, and images, in signalling their authenticity and enabling them to be used as money (Burnett, 1991, p. 29 ff.; Kemmers and Myrberg, 2011). In addition to their monetary function, coins have often assumed various secondary roles in different contexts. Finely crafted coins of precious metals were sometimes used as jewellery or amulets, or as grave goods. Their portability and durability made them an ideal medium for disseminating messages. Because of all these features, coins are a valuable source of historical information.

Although most of the coined money produced today has roots in the Western tradition originating in the ancient Mediterranean in the late 7th century BCE, another independent tradition of round metal coinage developed in ancient China in the 4th century BCE, influencing the coinage of East Asia (Grierson, 1975, p. 55 ff.; Schaps, 2004, pp. 232–3). The different geographic, cultural, political, and economic contexts in which these two inventions took place resulted in different materializations of the idea of coinage (Scheidel, 2008, 2010). While in the Mediterranean, coinage was largely struck on precious metals from the region's abundant mints, Chinese coins were made of bronze, replacing earlier bronze ingots shaped like spades and knives that were used as money. Moreover, Chinese coins were marked only by inscriptions stating the issuer and the value, unlike Mediterranean coins, which were stamped with figurative designs.

Ancient Mediterranean coins were collected and studied since the Renaissance. Their artistic quality and the variety of images depicting mythological characters or portraits of historical persons known from the rediscovered texts of classical antiquity has fascinated scholars and amateurs alike, and has contributed to the emergence of large museum collections, and of the discipline of numismatics (Elkins, 2009). Numismatics is a specialist discipline, focused mainly on managing collections and classifying coins by examining their technical features and designs, discussing their provenance and age, and recognizing patterns in production and style (Grierson, 1975; Kluge, 2016). In the last couple of decades, however, numismatists intensified their collaborations with related historical sciences, actively contributing to debates on the origin and use of coined money in different historical contexts and cultural settings, developing methods for reconstructing past political and economic institutions and networks, and emphasizing the value of coins as an abundant and multi-faceted historical source (Haselgrove and Krmnicek, 2012). In turn, archaeologists and historians are giving more attention to coins found in excavations or surveys. Knowing the archaeological and historical context of a single coin or of a coin hoard can add substantially to the validity of our interpretations of these artefacts, and improve our knowledge of the socio-economic circumstances of people living in a certain place in a certain historical period (Kemmers and Myrberg, 2011).

However, the majority of coins accumulated in private and museum collections around the world come from accidental finds or auctions, and do not have clear provenance, which makes them potentially unreliable as sources of information. Still, because coins are produced in series, and are preserved in sufficiently large numbers, they are well-suited for statistical analyses, which can account for the missing contextual information and allow us to extract as much information as possible from the objects themselves (Iossif, 2018a). Recent advances in the digitization and standardization of coin collections as a part of the digital revolution in the humanities has made them more available to interested amateurs and researchers from different disciplines. Openly shared online, such databases stimulate discussions about the challenges and possibilities that these new developments present for the documentation and curation of numismatic material, and about their potential for developing new analytical approaches.

The increasing popularity of digital technologies in cultural heritage management, history and archaeology has rekindled long-standing debates on theoretical and methodological approaches to historical artefacts. At the core of these issues is the perceived dichotomy between the humanities on one side, and the natural and social sciences on the other. Research in the humanities has traditionally been focused on the observation, collection, classification, and interpretation of various types of data, which is often contrasted with the research methods of the natural and social sciences, which use statistical models and measures to infer and explain general patterns in large data sets and test predictions derived from theory (Preston, 2014).

History and archaeology have both started from the antiquarian and culture-historical approaches of the 19th and early 20th century, which focused on constructing narratives about the past through conducting detailed studies of limited material evidence. While they can provide a deeper understanding of observed historical phenomena, and generate hypotheses about their causes, these data-driven, inductive approaches carry a risk of being overly subjective, hindering the possibilities for objective comparison of different views and testing of proposed causal relationships. In the 1960s, these traditional approaches were challenged by the emergence of the "New Archaeology" (processual archaeology), a new theoretical direction which aimed to make archaeology more "scientific" by using mathematical models to identify and explain processes behind the observed patterns of cultural change (Binford, 1962; Clarke, 1968). The views of the "New Archaeology" have been criticized as overly mechanistic and positivistic, overemphasizing functional and behavioural explanations, and relying exclusively on quantitative methods as the key to understanding the archaeological record. The alternative approach, termed post-processualism, stressed the importance of studying the interactions between societies and material culture inside their particular archaeological and historical context in an attempt to understand the meaning they had for contemporary societies (Hodder, 1991a; Shanks and Tilley, 1996).

However, the use of quantitative methods does not necessarily involve a commitment to processualism, positivism, or any other theoretical approach. Measurements have always played an important part in archaeological research, from constructing typologies of artefacts based on their shapes and sizes, to radiocarbon dating, and analyzing material and biological remains through a combination of methods from geosciences, chemistry, biology and genetics, aiming to understand the relationships between people, objects, and the environment. Mathematical models and statistical analyses provided an additional opportunity to overcome the limitations of fragmentary data, reconstruct the movements of people and objects through space and time, and test the plausibility of proposed theories (Shennan, 1988, p. 3 ff.). Today, most archaeologists around the world tend to be pragmatic, and choose the approach suitable for dealing with the specific conditions of their work in local contexts, or develop their own theories and methods (for general overviews of archaeological theory see Trigger, 2009; Bintliff, 2006; Bentley et al., 2009; Gardner et al., 2013; cf. Hodder, 1991b; Marciniak and Yalman, 2013).

Classical archaeology presents a specific case, because of its deep roots in the humanistic disciplines of art history and classical philology, and its focus on texts and objects produced in the Greco-Roman Mediterranean between the 8th century BCE and the 5th century CE (Millett, 2012; Snodgrass, 2012). The advantage of having primary sources at their disposal – literary texts, inscriptions, papyri etc. – made classical archaeologists less reliant on developing complex theoretical frameworks to interpret their findings. Instead, they tend to be rather cautious and reserved towards adopting new theoretical approaches and methods (Morris, 2006). Over the past half century, however, a growing interest in the lives of ordinary people in the Greco-Roman society has led classical archaeologists to conduct extensive field surveys and focused systematic excavations, revisit large collections of objects and texts accumulated thorough the years, and combine traditional methods and practices with theories from social sciences and novel analytical approaches (Morris, 2006; Snodgrass, 2000; Gill, 2009; Alcock and Osborne, 2012; Haggis and Antonaccio, 2015; Canevaro et al., 2018; MacKinnon, 2018; Small, 2018).

In the last couple of decades, discussions on the use of computational methods and statistical analyses in social sciences and humanities created a movement towards more open, methodologically sound and collaborative research paradigms, and towards the publication of openly shared, findable, accessible, interoperable and reusable (FAIR) data, including metadata such as coding guidelines (Harrower et al., 2020). Projects creating and managing large databases of cultural data focused on developing reliable and widely accepted standardized data formats, concepts, and ontologies, as well as strategies to overcome data uncertainty by combining inputs from multiple sources or expert coders, and factoring in the level of agreement between them (Huvila, 2019; Slingerland et al., 2020). However, digital databases and standards for accurately representing archaeological data have a long but somewhat neglected history, rooted in the structuralist and logicist approaches of the mid-20th century. Discussing his proposed analytical framework, David Clarke stressed the importance of well-defined descriptions of archaeological material and concepts, as a prerequisite for conducting the quantitative analyses necessary for the accurate interpretation of observed patterns and processes (Clarke, 1968; cf. Lycett and Shennan, 2018). French archaeologist Jean-Claude Gardin investigated the process of theory formation and interpretation in archaeological research, and led an initiative aiming to develop standardized relational "metalanguages", based on interconnected concepts, to describe archaeological data, laying the foundations of archaeological computing (Gardin, 1958; cf. Moscati, 2016; Dallas, 2016).

Large digital databases enabled historians and archaeologists to test hypotheses concerning historical dynamics on a much bigger scale, using statistical analyses, placing individual historical sources and artefacts in a wider perspective. However, while the value of studying the past from the perspective of social sciences using "big data" has been recognized by traditional historians and archaeologists, some remain sceptical of the usefulness and validity of such approaches, criticizing them for making broad, overly general claims based on fragmentary and scarce source material, while overlooking important details, issues which they argued could be addressed with classic comparative approaches (for the overview of debates see Anderson, 2007; Lemercier and Zalc, 2019). In order to take full advantage of digital resources and novel research methodologies, and avoid misinterpretations or unfounded claims, it is necessary that historians and archaeologists collaborate closely with experts from other disciplines, develop research projects that are grounded in theory, and follow good scientific practice, clearly stating their methodological commitments and objectives.

As a scientific discipline reconstructing past lives from the material remains of people, objects and buildings, texts and environmental traces, archaeology has always been an interdisciplinary science, integrating elements from the humanities, as well as the social and natural sciences. Such an interdisciplinary approach has been taken here. Rather than strictly adhering to a particular theory or school of thought, the work presented in this thesis integrates different theoretical perspectives and methods from archaeology, cultural evolution, information theory, and cognitive science, in an attempt to find new ways to study coins as a system of objects combining carefully designed physical features, text, and graphic representations to convey economic, political, and cultural information. The general aim of this project was to try to understand how different historical circumstances combined with underlying mechanisms of human cognition influenced the way coins were made and used in the early days of their evolution, as well as to learn how coins record and transmit information on monetary value.

The remainder of this introductory chapter will give a short overview of the broader topic of the origins of money and coins (section 1.2.1-3), before focusing more narrowly on different approaches to the function and meaning of ancient coins and their design (section 1.2.4), and discussing relevant theoretical and methodological background of the project, based in the fields of information theory and cultural evolution (sections 1.3 and 1.4). Section 1.5 concludes with an overview of the three chapters that form the main part of the thesis.

1.2. Coins and money

The question of the origin of coins is closely tied to a series of still ongoing debates in economics, sociology, and anthropology, concerning the origin and nature of money. These discussions tend to revolve around two main topics: the material and symbolic features of money (considering both the physical money, and money as an abstract concept), and the respective role of political authority and market exchange in the emergence of money and its practical use (Hart and Ortiz, 2014, pp. 465–8; 471 ff.; Nelms and Maurer, 2014, pp. 37–43).

1.2.1. Money in economics and anthropology

Two leading theories on the origins of money dominate Western economic history. The first, "commodity theory" of money proposes that money originated as a way to regulate barter exchanges of various commodities in markets. Already posited by Aristotle (*Politics*, 1.1257α; transl. H. Rackham 1932) and the father of modern economics, Adam Smith (1893 [1776]), this view has been refined in the 19th century by William Stanley Jevons (1875) and Carl Menger (1892). They both defined money in terms of its three main functions: unit of account, store of value and medium of exchange. Money was understood in material terms, as a commodity possessing an intrinsic value, suitable to be used as a universal medium of exchange. Precious metals, silver and gold, were recognized as the most appropriate universally accepted commodity to be used as money due to their portability, divisibility and durability. This "metallist" view has been challenged by Georg Friedrich Knapp (1905), who proposed that instead of originating from barter, money originated from state-imposed regulations and taxation, and its value does not lie in the commodity used as money, but in the power of the authority, which establishes the unit of account and guarantees the value of medium of exchange. The reliance on the gold standard as the basis of international monetary exchange has long given prominence to metallism as the leading theory of money. However, with the prevalence of state-backed fiat money, credit economy and digital banking, Knapp's "chartalist" theory has influenced modern economists to stress the role of political authority ("state") in the emergence of money, through debt and credit mechanisms (Wray, 2004; Wray, 2012; cf. Ingham, 2004; Graeber, 2011).

Discussions on money in anthropology have focused on defining the concept of money and its significance in society (Hart, 2005; Hart and Ortiz, 2014; Maurer, 2006; Nelms and Maurer, 2014). Classical theories of money in social sciences by Karl Marx, Georg Simmel and Max Weber have largely been focused on the Western capitalist economy, discussing the ways money, presenting a means to quantify value of both commodities and services, shaped the lives of individuals, and society as a whole (Hart, 2005, p. 167 ff. Hart and Ortiz, 2014, pp. 468–9; Maurer, 2006; Nelms and Maurer, 2014, pp. 43–6). When they started studying exchange systems among non-Western populations, anthropologists were struggling to integrate them with the commonly accepted view of money as commodity functioning as a medium of exchange, unit of account and store of value. At the foundations of economic anthropology is the debate between Bronisław Malinowski (1932 [1922]) and Marcel Mauss (1990 [1925]) over the criteria that make a certain commodity "money". Malinowski studied the exchange network of Kula valuables in the Trobriand Islands archipelago of Papua New Guinea. Although they represented value, these items were not exchanged on a market, but in situations governed by complex social rules, which is why Malinowski thought they could not be considered as "money" or "currency". Mauss, on the other hand, proposed that valuables exchanged in economies that are not based on market exchange but, for instance, on the reciprocal exchange of gifts, can also be seen as a type of money (Hart and Ortiz, 2014, pp. 467–8; cf. Nelms and Maurer, 2014, p. 42).

Building on these ideas, Karl Polanyi (1957, 1968, 2001 [1944]) proposed an alternative view on economy based on subsistence needs ("substantive" meaning) rather than the rational choice of maximizing utility ("formal" meaning). In his view, the economy comprised multiple forms of modes of exchange (from reciprocal gift exchange and redistributive economies to market exchange), and multiple forms of money, defined by their function: general-purpose money, which fulfils all monetary functions (means of payment and exchange, unit of account and a standard of value), and special-purpose money, which is used only in specific social contexts. Polanyi's theories were further developed by his colleagues. Paul Bohannan (1955) investigated different spheres of exchange among the Tiv in Nigeria. George Dalton (1965) discussed the notion of "primitive money" in terms of the exchange media ("money stuff"), and their functions in exchange, arguing against a comprehensive definition of money, instead focusing on its functions in different contexts. Helen Codere (1968), on the other hand, expanded Polanyi's view of money as an abstract symbol, given physical form in different "money-stuffs" which symbolize monetary value and form a system comparable to other symbolic systems, such as numbers, measurements, and writing. The views of the "Polanyi school of anthropology" were criticized by the economist Jacques Melitz (1970), who argued that there is no difference between all-purpose (Western) and special-purpose ("primitive") money as described by Polanyi, because there are limits to what even Western money can buy. He pointed out a difference between units of account, which can be agreed upon in order to lower transaction costs, but are not necessary for the exchange of various goods, and media of exchange, which he argues are more relevant to the definition of "money". Melitz further criticized Polanyi and his colleagues for trying to adapt classical economic theory to fit different cultural contexts by introducing the concept of "primitive" money to describe monetary objects that failed to fulfil all economic functions of money. Instead, Melitz proposed that the focus of research on economic systems should be on the tendency to maximize utility and gain in the context of a particular society, regardless of their use of media of exchange (cf. Hejeebu and McCloskey, 1999).

The impact of Western money on traditional exchange systems in the colonial period, the existence of different "spheres of exchange" and different uses of money in postcolonial societies were discussed in a collection of papers edited by Jonathan Parry and Maurice Bloch (1989). It marked a shift from focusing on the concept of money and its functions from the perspective of Western monetary economy towards a more pragmatic view of money, investigating the multiple forms, meanings and uses it can assume in a particular context (Nelms and Maurer, 2014, p. 47). Keith Hart argued that neither the "commodity" theory of money, which emphasizes the materiality of money and the influence of exchange and markets in its emergence, nor the "credit" theory, which sees money as an abstract concept of value based on state power and public trust, are adequate to address the complex nature of money (Hart, 1986, 2005). He proposed a unified approach to the theory of money, illustrated by the two sides of a contemporary coin: "heads" symbolizing the power of political authority, and "tails" stating its value as an exchange medium. As physical monetary objects bearing symbols of "states" and "markets", coins illustrate the dual nature of money – its materiality and its symbolic value.

1.2.2. The ancient economy

Economic and anthropological theories of money have influenced research on economic history of the ancient world. In the first half of the 20th century, ancient historians attempted to assess the scale of the economies of ancient Greece and Rome in comparison to contemporary Western economies. Some scholars believed ancient economy to be similar to modern ones, only operating on a lower scale, whereas others maintained that ancient economies were comparatively primitive, largely based on self-sufficient households, engaging mainly in the redistribution of goods, gift exchange and small-scale market exchange. This debate between the "primitivists" and "modernists" lasted for almost a century (Morris, 1999; Smith, 2004; Bresson, 2015, p. 29 ff.; cf. Finley et al., 1979).

Moses Finley, influenced by the writings of Karl Polanyi and Max Weber, published his *Ancient Economy* (1999 [1973]), where he argued that the focus of research on ancient economy should be on the structure of social and political institutions and values, rather than production and exchange, which was the focus of previous debates. He was against applying modern economic theories and models on the ancient world. In his view, the special status of free citizens of Greek and Roman states was a key factor that led to the creation of closed economies of "consumer cities", whose citizens lived from exploiting the adjacent countryside, and did not engage in long-distance exchange. Finley's views have been highly influential for several decades, but were also criticized for underestimating the scale of trade and market exchanges apart from those relying on social relations and agriculture. Others thought that it was too simplistic, attempting to provide an overview of over a millennium of ancient Mediterranean history by generalizing over fine-grained data and disregarding many examples countering his theory (Bresson, 2015, p. 37 ff.; Morris, 1999; von Reden, 2010, p. 9 ff.).

Despite these issues, Finley's work inspired further discussion on the suitable approaches to ancient economy, weighing out the benefits and possible dangers of using modern economic models and comparative examples from anthropology to interpret the relatively scarce sources on production, exchange, and consumption in the ancient world. Combining the results of in-depth analyses of historical sources and archaeological data with models adapted from social sciences, ancient historians managed to overcome the limitations of the available information and infer global diachronic patterns in the development of the ancient Greek and Roman economies (Kim, 2001a; Morris et al., 2007). The availability of new material and analytical techniques enabled researchers to revisit questions on the nature and structure of ancient Greek economy and the underlying factors of its transformation from the end of the "dark age" in the 8th century until the end of the Hellenistic period in 1st century BCE (Cartledge et al., 2001; von Reden, 2003; Morris, 2004, 2005; Osborne, 2007; Davies, 2007; Möller, 2007; von Reden, 2007; Reger, 2007; Scheidel et al., 2007; Bresson, 2015; Ober, 2010, 2015; cf. de Callataÿ, 2014). Keeping in mind that these large-scale models are only approximations, based mainly on the few most well-known cities in the ancient world like Athens and Rome, there is still enough evidence to suggest that the standard of living in the Mediterranean improved substantially from the rise of the Greek city-states in the Aegean and throughout the Mediterranean in 8th century BCE until the fall of the Western Roman Empire in 5th century CE (cf. contributions to Manning and Morris, 2005; Scheidel et al., 2007). Based on these estimates, most historians agree that even though this economic growth was rather modest in comparison to the modern times, it nonetheless had a significant impact on the livelihoods at the time.

However, debates remain on the principal forces driving the intensification of ancient economies, focusing on the respective role of market exchange and long-distance trade on the one hand, and state initiative and institutions on the other, while acknowledging that this role changed in different socio-cultural contexts through history (Morris et al., 2007, p. 10 ff.; Scheidel and von Reden, 2012; Harris and Lewis, 2015). In the context of these discussions, the causes and the impact of the invention of coined money, its relation to other commodities involved in exchange, and the level of monetization of ancient economies have been particularly important.

1.2.3. Origins of coins

The invention of coins has undoubtedly transformed the history of money and exchange. Coins are often cited as the first objects that were used as universal units of account, means of exchange and store of value, embodying all three functions of money proposed by the traditional economic theory (Bresson, 2015, p. xxi ff.; Grierson, 1975, p. 6; Osborne, 2007; Schaps, 2004, pp. 1–7). There were other commodities, from cattle to various luxury metal objects, such as the bronze tripods and iron spits of Homeric and archaic Greece, that were used to quantify and store value, and to mediate exchange through the Mediterranean, but in a limited capacity when compared to coins (Bresson, 2015, p. 368 ff.; Schaps, 2004, p. 34 ff.; 222 ff.; Seaford, 2004, pp. 1–9). Depending on their theoretical approach, historians tended to regard these commodities as pre-monetary media of exchange, thus applying the concept of money only to coins (van Alfen, 2018a). In recent years, under the influence of the new directions in the economic and anthropological theory of money and archaeological discoveries, more attention is being paid to precious metal ingots and cut-up scrap pieces (*Hacksilber*) and their role in ancient economies (Haselgrove and Krmnicek, 2012; cf. Balmuth et al., 2001; Thompson, 2003; Kroll, 2008). The fact that there were other kinds of money used before and in parallel with coins opens the question of why coins were produced, and how they became widely used.

The earliest coins, issued by the Lydian kingdom and by Ionian city-states on the coast of Asia Minor, were found in deposits under the temple of Artemis in Ephesos, dated to the second half of the 7th century BCE (Weissl, 2005). These coins were made of electrum, an alloy of silver and gold, shaped in small lumps, and stamped with punch marks and figurative designs. Several theories have been put forward concerning who and why produced the first coins. Most early theories followed Aristotle (*Politics*, 1.1257α-β; transl. H. Rackham 1932), who believed that coins were introduced as a way to facilitate trade by introducing precious metal pieces of standardized weight as a convenient medium of exchange, and by marking them to avoid weighing at each transaction (see summary in Wallace, 1987). This argument was challenged by the studies of coin hoards, which suggested that early electrum coins circulated only in a limited area, and were mostly produced in large denominations unsuitable for market transactions (Cook, 1958; Kraay, 1964). Another issue was the choice of metal. Early analyses of electrum from coins and natural sources of electrum in Asia Minor have shown that the alloy was highly variable, and that it could have been difficult to determine the gold/silver ratio in the bullion (Wallace, 1987). This prompted theories arguing that coins were developed as a way to deal with the variable nature of electrum bullion. Issuers would impose the standard exchange value for coins by stamping them with a mark which signified that coins of a certain weight, regardless of their metal content, would be accepted as valid means of payment (Wallace, 1987; Le Rider, 2001). Even though the multitude of different images on early coins led some to propose that they were issued by merchants or "bankers", most numismatists agree that the authority of the monarch or the city-state government was more likely to control the coin production and impose the variable alloy as the means of exchange (Wallace, 1987; Seaford, 2004, pp. 134–5).

While it is still unclear who exactly minted the first coins and for what purpose, recent studies combining archaeological and numismatic insights helped to shine new light on some questions on the nature of early coins (de Callataÿ, 2013; Konuk et al., 2012; van Alfen et al., 2020). A careful examination of more than three thousand early electrum coins known today reveals that these coins were produced according to a well-defined system of weight standards, in many different fractions, featuring several hundred different image types (Fischer-Bossert, 2018a; Velde, 2014). Recent metal analyses seem to suggest that, although electrum can occur naturally, the alloy used for minting coins was artificial, and combined in relatively stable ratios, which highlights the technical competence of Ionian and Lydian minters, and also implies that the alloy could have been manipulated for extracting profit from issuing coins (de Callataÿ, 2013; Fischer-Bossert, 2018a; Konuk et al., 2012). The level of standardization, the choice of alloy over the pure metal, and the use of figurative stamps to certify their authenticity set these coins apart from weighed silver bullion (de Callataÿ, 2013). However, the gold content made electrum more valuable than silver, so even the smallest fractions were too valuable to be used for everyday purchases, and costly to produce, which questions their profitability (Bresson, 2006; Schaps, 2004, p. 97). Also, the multitude of different types of stamps exceeds the number of polities that could have produced these coins in the period between the end of 7th and the mid-6th century BCE, which further complicates the inquiry into the origins of coinage (de Callataÿ, 2013; Fischer-Bossert, 2018a).

Recently, Peter van Alfen (2020) has warned against the anachronistic view of "the state" as a homogenous entity with a monopolistic impact on ancient economy, and argued that, instead of economic gain, the motivation for producing coins in the period of formation of polities and empires has been primarily political, allowing individual competitors (monarchs or tyrants) and ruling elites to gain the influence necessary to negotiate with their competitors and the people, and secure political control and stability (cf. similar argument in MacDonald, 1916, p. 12 ff.). On the other hand, Alain Bresson prioritized markets as the driving force of the economic change that gave rise to coinage, by creating a space for public exchange, as opposed to state expenditure and religious donations (Bresson, 2006). Still, he did not deny the role of the state in the distribution of coins in circulation, which helped to trigger the production and trade necessary for the emergence of markets (Bresson, 2015, p. 367 ff.). It is likely that a combination of political and economic factors played a role in the emergence of coinage in the ancient Mediterranean. Still, more systematic, interdisciplinary research is necessary to fully understand the causes of this invention.

In the middle of the 6th century BCE, electrum coins were replaced by the bimetallic system of gold and silver coins introduced by king Croesus in Lydia, making them more practical to use and produce, and arguably more trustworthy, at the expense of the profit derived from overvaluation (Bresson, 2009; van Alfen, 2020). Although some Greek polities on the coast of Asia Minor kept using electrum coinage for the next couple of centuries, city states in the mainland Greece started producing silver coinage which soon spread among Greek cities (*ἀποικίαι*) all over the Mediterranean. It is estimated that by the end of the 6th century over forty Greek city-states produced their own coins, with this number growing rapidly in the following decades (Howgego, 1995, p. 5 ff.; Osborne, 2009, p. 237 ff.; Schaps, 2004, p. 104 ff.; Hansen and Nielsen, 2004, pp. 144–149; Index 26.; von Reden, 2010, p. 71; cf. Ober, 2015, p. 39 ff.). Neighbouring people – most notably the Phoenicians – were slower to adopt coinage despite their prominent role in Mediterranean long-distance trade (Howgego, 1995, p. 1 ff.; Schaps, 2004, pp. 106–7, 2014). However, not all Greek polities issued coins, and the reasons for producing and using coins seem to be complex. Although an important technical precondition, the availability of silver bullion does not seem to be the key factor for the production of coinage. Although they traded with silver, Phoenicians did not mint it into coins. On the other hand, many Greek cities which did not have access to silver mines still minted coins, acquiring bullion through different means, from trade to war spoils (Bresson, 2015, p. 374 ff.; Howgego, 1990, p. 4 ff.; Schaps, 2004, p. 104 ff.).

The emergence and spread of silver coinage seems to be a primarily Greek invention and phenomenon, even though the idea of coinage might have originated in the Lydian royal mints (Schaps, 2014). The production of coins and their use are embedded in the context of the emergence of Greek city-states (*πόλεις*), and the increasing development of political and economic networks between them, from the 6th century BCE onwards (Howgego, 1995, pp. 12–18; Osborne, 2009, p. 242 ff.). Examining the evidence from known coin finds and deposits (hoards), which implied that the coins were produced primarily in large denominations and mostly used locally inside the limits of a city-state, Colin Kraay suggested that the early coins were issued by city-states for making standardized payments, comprising both their "state expenditure" (hiring mercenaries and various workers), and their debts towards the polity, e.g. taxes or tribute (Kraay, 1964; cf. Cook, 1958; Kraay, 1976, p. 317 ff.). It was later shown that the numismatic evidence has been biased by inefficient techniques for recovering smaller coins from archaeological contexts, combined with the collectors' lack of interest in base metal coinage (made of bronze, copper, lead, etc.). Changes in archaeological practice, increased interest in coins, and the introduction of metal detectors have transformed our understanding of ancient coinages, showing that more small change has been produced very early on by multiple cities, and that some coins have indeed travelled very far (Howgego, 1995, pp. 6; 88–110; Kim, 2001b, 2001a). Some economically and politically powerful polities, notably Aegina, Corinth and Athens produced large quantities of coins of consistent quality which became widely accepted as a means of exchange between different city-states (Howgego, 1990, 1995, p. 27 ff.; Schaps, 2004, p. 106 ff.). However, most city-state issues were rather small and sporadic, not always covering a wide range of denominations, and were based on different weight standards, which complicated the use of coins for inter-polities trade (Carradice and Price, 1988, pp. 22; 90–6; Osborne, 2007). Long-distance trade in the Mediterranean was thriving long before the coins were invented (Schaps, 2004, p. 195 ff.). They seem to have been issued by the city-states primarily for their own purposes, rather than to facilitate trade, but the introduction of coined money stimulated the emergence of markets and various political and economic institutions (Osborne, 2007; Schaps, 2014; von Reden, 2010, p. 12 ff.). The increasing needs of the fast-urbanizing polities depended on the contributions of wealthy landowners for its building projects, ships, and military expenses. These contributions were paid in coins acquired from the market, where agricultural products were sold to soldiers, workers and public servants who were paid by the state (Osborne, 1991; Martin, 1996; Osborne, 2007; Schaps, 2004, pp. 172–3).

Although coins were used in many spheres of both public and private life in Greek polities, they did not entirely replace other forms of exchange (Davies, 2007; Schaps, 2004, p. 194 ff.; von Reden, 2003, 2010). The circulation of coins both inside and outside of the polis was regulated by well-calculated monetary policies, which were meant to bring profit to the polity. These policies are mainly known through inscriptions and literary sources (Howgego, 1990). Plato (Laws 5.742; transl. R. G. Bury 1926) noted the differences between the local coinage of the polis (*νόμισμα ἐπιχώριον*), the official legal tender whose value has been guaranteed by the state, and the coinage of other polities (*νόμισμα Ἑλληνικόν*), which either had to be exchanged for the local coinage, or to be traded on the basis of its bullion value on the market, without any guarantee that it would be accepted (cf. discussion by Meadows, 2009). Some city-states tried to overcome the disadvantages of different monetary policies and to stimulate monetary exchange by aligning on the same weight standards and creating common exchange networks with their neighbours or political allies, while others created closed monetary systems where the political elites exercised more control over the value of their coins, sometimes at the expense of their quality (von Reden, 2010, p. 65 ff.; Psoma, 2015; Picard, 2007; Mackil and van Alfen, 2006; Economou et al., 2015; van Alfen, 2018b).

The early history of coinage seems to have been shaped by the complex interplay of the political authorities of city-states and of the economic forces of the markets, symbolized by the *agora* as a place of both political and economic exchange between the citizens of a *polis* (von Reden, 2007, 1997). Recent series of works on the origins of coinage and money in the ancient world has focused on coins from a socioeconomic perspective, discussing the ideological aspects of coins, their meaning in different spheres of exchange, and their influence on the Greek society (Kurke, 1999; von Reden, 2003; Schaps, 2004; Seaford, 2004; cf. review by Peacock, 2006). Despite being criticized by some for a lack of conceptual clarity, and for relying on textual sources instead of numismatic evidence, these studies have highlighted important aspects of coins that made them stand out as a special form of money (Morris, 2001; de Callataÿ, 2011; van Alfen, 2018a).

Richard Seaford (2004), in his definition of money, follows the neochartalist economic theory, seeing money as a social construct, representing the means to meet a certain obligation (cf. Graeber, 2001, p. 103 ff.; Ingham, 2004). Focusing on coins as a physical manifestation of an abstract concept of "money", he expands the classic functionalist economic definition, emphasizing the role of the state in guaranteeing the acceptance of coins as legal tender. By coining money, the state authority could control the exchange of precious metals. An officially issued silver coin was no longer just a commodity whose value was dependent on market prices or social status of the user, but a trustworthy medium of exchange established by a convention. The practice of minting coins also allowed silver pieces to be counted, rather than weighed, making exchange more impersonal and universal (Seaford, 2004, pp. 1–9; 16–20). Confidence in the value of coined money as proclaimed by law enabled coins to function as the first form of fiduciary money: a coin's value as a medium of exchange did not always match the intrinsic value of its metal (Seaford, 2004, pp. 136–46; cf. Schaps, 2004, p. 30 ff.; Peacock, 2006). Already present in early electrum and silver coinage, this characteristic is even more evident in bronze coinage, which was introduced in the middle of the 5th century BCE in the Greek polities in southern Italy and

Sicily, and eventually adopted as a norm for small change in many other polities, replacing impractical small silver denominations (Seaford, 2004, p. 145; von Reden, 2010, p. 32 ff.; cf. Bransbourg, 2011, pp. 90–1; van Alfen, 2018a, p. 496).

The innovations of Greek polities in the use of different metals to produce coins, and in creating policies and institutions to establish the control over their value helped transform the monetary economy of the ancient world (Schaps, 2014). Although the level of fiduciarity of the early coins and the functions they fulfilled can be debated, what made Greek coins (*νομίσματα*) different from other types of currency (*χρήματα*) was their legal status (Gr. *νόμος* = law), which made them the political device as well as economic medium, an embodiment of the power of money (van Alfen, 2018a, p. 506; cf. Seaford, 2004, p. 16; Schaps, 2004, p. 16; von Reden, 2010, p. 6 ff.). This power manifested itself through a mark of the authority stamped on the pre-weighed piece of metal, which transformed it into a coin by guaranteeing its quality and value (Seaford, 2004, p. 126; Schaps, 2014; cf. Spier, 1990; Bresson, 2006; de Callataÿ, 2013).

1.2.4. The role of images

Figurative designs remained a central distinguishing feature of western coinage to this day, assuming different functions and meanings in different historical and cultural contexts. From their beginning in the late 7th century BCE, the coins of Greek polities have shown a remarkable diversity of motifs and motif combinations, as well as artistic and technical quality, which attracted Renaissance collectors and prompted theories on their function and meaning (Elkins, 2009; de Callataÿ, 2016). Early numismatic compendia, which systematized distinct types of coin images, most notably *Doctrina numorum veterum* by Joseph Hilarius von Eckhel, interpreted them as representations of local mythology, geography, and economy. In the 19th century, Thomas Burgon attempted to find a general explanation for these images, proposing that the designs of Greek coins were “religious” in character, because many depict mythological motifs, and bear portraits of gods and heroes (Burgon, 1836). This view was supported and expanded by Ernst Curtius, who believed that the earliest coins were produced in temples, and were therefore connected to religious cults, before control over coin production had been taken over by civil authorities (Curtius, 1870). William Ridgeway suggested an alternative explanation, arguing that the objects and animals appearing on coins evoked pre-monetary media of exchange (Ridgeway, 1892). Both the “religious” and “commercial” theory were criticized from the beginning of the 20th century as speculative attempts based on selected examples, which could not provide a satisfactory explanation for the diversity of images found on early coins (MacDonald, 1905, pp. 15–36; cf. Head, 1911, p. lv–lvi). In his influential manual of Greek coins, Barclay Head suggested that the frequent representations of divinities and heroes should not be interpreted as "religious" images, but rather as "guardians" of the validity of official coinage, meant to discourage malpractice (Head, 1911, p. lviii). George MacDonald put forward a more general interpretation of coin designs as official marks of the issuing state, highlighting the role of political authorities in the regulation of coin production (MacDonald, 1905, 1916; cf. Head, 1911, p. lvi–lx). His argument was based on the similarity between coins and seals with figurative designs that were used to mark private and public ownership, and authenticate contracts and transactions in Mesopotamia and the Aegean, long before coins were invented. The fact that seals and coins shared similar engraving techniques, and that the same workers were probably involved in the production of coin dies, gems, and signets, as well as a partial overlap of the iconographic repertoires of coins and seals, suggest that the practice of stamping coins with graphic designs has likely developed from the use of seals (Head, 1911, p. lvi; MacDonald, 1905, pp. 43–48; Spier, 1990, p. 108 ff.; Seaford, 2004, p. 115 ff.).

While equivalent representations of gods, heroes, mythological creatures, animals, plants, and objects can also be found on other contemporary material, like painted pottery, metalwork and sculpture, on seals and coins these images assume the role of emblems, i.e., signs used for representing identities or affiliations of individuals or groups, similar to flags, badges, military insignia or heraldry (Davis, 1985; Spier, 1990; cf. de Callataÿ, 2016). Seals most commonly represented an individual (a private person, an official or a ruler), and served to indicate their authority in all kinds of legal and commercial matters. However, independent Greek polities also had their public seals, featuring depictions of attributes of local deities (often animals or objects), prized local products, or visual puns to the city's name, which are understood as emblems (*παράσημα*) of the polity (MacDonald, 1905, p. 60 ff.). These emblems were found on official inscriptions, weights, measuring cups and even products such as amphorae (Killen, 2017). By the end of the 6th century BCE, city emblems were adopted as a main design ("type") on the coinage of most city-states (Head, 1911, p. lvii–lviii; Kraay, 1976, pp. 2–5; Spier, 1990; Weir, 2010). At the beginning of the 4th century BCE, under the influence of popular Athenian coins featuring the patron goddess of the city, many polities included a portrait of a deity or mythological hero as the main design on the obverse (front side) of their coins, while emblems were either moved to the reverse side of a coin, or completely disappeared (MacDonald, 1905, p. 134 ff.; Picard, 2018). Although coins carried recognizable marks of their issuing authority, the main purpose of these marks was to authorize the use of the coin as a medium of exchange, rather than to claim ownership, as was mostly case with seals and signets (Seaford, 2004, p. 118 ff.).

The political interpretation of coin designs as representations of autonomy, power, control, and legitimacy of the city-state was prominent in the next decades, but it has since been pointed out that, just like the reasons to produce coins, the choice of designs depended on economic reasons, as well as political ones (Finley, 1999 [1973], pp. 167–69; critique in Martin, 1985; cf. Howgego, 1990; Martin, 1996). More recently, coin designs are seen as an indication of monetary policies and of the power of the issuing authority, which controlled the production of valid coins (van Alfen, 2012; de Callataÿ, 2018; Picard, 2018).

Most polities which produced and used coins focused on enforcing the acceptance of their own local coinage, and limited the use of foreign coinage as legal tender, requiring it to be either exchanged for local coins, or reminted (Howgego, 1990; Meadows, 2009; Fischer-Bossert, 2018b). Still, fine silver coinage of economically and politically powerful polities, such as Athens, Corinth and Aegina, came to be used as a sort of "international" currency, and these coins became known by their recognizable central motifs as "owls", "colts" (Pegasi) and "turtles", respectively (Grierson, 1975, p. 14; Carradice and Price, 1988, pp. 57–8). The stable designs of the exported coins could be understood as marks of provenance and as a guarantee of their unchanging quality, suggesting that these images had economic relevance (Spier, 1990; Melville-Jones, 2006; Weir, 2010; cf. Wengrow, 2008). Smaller denominations, usually limited to local use in the sphere of influence of the issuing authority, often display more variability in their images than larger denominations, which were more likely to be exchanged outside of the polity because of their greater intrinsic value (Head, 1911, p. lxiv–lxv; Weir, 2010). However, by the end of the 6th century BCE, most Greek polities consistently minted distinct images on their silver coins, even if these coins rarely circulated outside of the polis or the surrounding region, which means that external exchange was not the only reason for producing coins with uniform designs (Weir, 2010). Variable designs and secondary motifs ("symbols") are often interpreted as marks of the officials responsible for coin production, as marks of different coin series, or even different mints or workshops producing coins of the same authority, depending on the specific historical context (Kraay, 1976, pp. 4–5; de Callataÿ, 2012). However, there are cases when variations in coin designs seem to indicate different denominations, even though explicit marks of value were rare on the early Greek coins, appearing first on the bronze coinage of the Sicilian cities in the latter half of the 5th century BCE, and then on the small bronze coins in the 4th century BCE (MacDonald, 1916, pp. 132–133; Kraay, 1976, pp. 4; 7–8; Carradice and Price, 1988, pp. 101–2; Weir, 2010).

In the absence of an inscription stating the name of the issuing city-state, graphic designs were, apart from the weight standard and metal, a key distinguishing feature that enabled the users to recognize valid coins of their own local coinage and coinage of other polities, and also to detect potential counterfeits (Meadows, 2009). Although coin issuers tended to choose distinctive designs, the coinage of some regions displays a certain level of thematic or stylistic similarity, which can be attributed to the relative homogeneity of Hellenic culture and its shared iconographic repertoire (MacDonald, 1905, p. 15; cf. Rutter, 2000). Coin designs were also imitated. The reasons were multiple: signalling political allegiance between mother cities and their colonies, identifying the members of a political or monetary alliance, as a sign of dominance of one polity over another, or as an attempt to make economic gains from adopting the images of well-known and trusted coinage (e.g. Athenian owls), to more technical reasons, such as sharing dies or minters, or purely because of aesthetic preferences, selecting images designed by skilled masters, depicting famous themes or works of art (van Alfen, 2005; cf. Papadopoulos, 2002; Mackil and van Alfen, 2006; Filocamo, 2016; Wahl, 2017; Puebla Morón, 2018; Fischer-Bossert, 2018b, 2018c). In response to imitative and counterfeit coinage, some polities passed laws intended to regulate their circulation, and introduced the institution of coin-proofers (*δοκιμαστές*) who would decide on the acceptability of coins according to their metal quality, weight and design (van Alfen, 2005; cf. Meadows, 2009; Weir, 2010). Possible confusion was additionally avoided by the introduction of inscriptions denoting the coin's issuer (a polity or an individual) (Head, 1911, p. lxiv ff.; Kraay, 1976, p. 5 ff.). However, this became a consistent practice only in the 4th century BCE (Carradice and Price, 1988, pp. 57–8; Weir, 2010).

Current consensus on the role of coin designs moves away from the Aristotelian "metallist" view of the coin's engraved mark (*χαρακτήρ*) as a guarantee of the quality and the weight of the coined silver, closer to the "neo-chartalist" abstract definition of money as a social convention, recognizing the designs as official symbols, meant to inspire trust in the power of the authority and in the monetary value represented by the coin (Howgego, 1995, pp. 28–9; Seaford, 2004, p. 136; Cribb, 2009; Papadopoulos, 2015; de Callataÿ, 2018; cf. Graeber, 2001; Ingham, 2004). Even though ancient texts present a good source for understanding the attitudes of ancient issuers and users towards coin designs, this evidence is often fragmentary (Spier, 1990; Elkins, 2009; Weir, 2010; cf. Seaford, 2004). Instead, research has turned to images themselves. The attempts to decipher the meaning of the "pictorial language" (*Bildsprache*) of motifs have been more successful in the context of the Roman Republican and Imperial coinage, which often included political messages (Alföldi, 1999; Wolters, 1999; Hölscher, 2004; cf. Elkins, 2009; Krmnicek and Elkins, 2014). In the case of Greek coinage, mostly produced by a multitude of independent states connected through complex political and economic networks and sharing a similar culture, the meaning and function of coin imagery is more complicated and still largely debated (Weir, 2010; Rutter, 2000; Wahl, 2017; cf. Ritter, 2002). Another line of research on the designs, based on semiotics, focuses on the structure of images and the way they connected through time and space, using linguistic analogy of an "iconic language of coinage" (Pérez, 1985; Caccamo Caltabiano, 2018; cf. Le Rider, 1975).

The availability of new material and methods has rekindled interest in coins and their designs beyond the numismatic circle in recent years. Applying quantitative methods over large samples of coins from museum collections, archaeological excavations and chance finds, combined with critical examination of the literary sources, has provided a way to study coins in their larger numismatic, archaeological, and historical context (Elkins, 2009; Kemmers and Myrberg, 2011; Krmnicek and Elkins, 2014; Iossif and van de Put, 2016). Adopting the concept of "object biographies" (cf. Kopytoff, 1986), a closer attention has been paid to the various contexts a coin has passed through on its way from the mint to its final finding spot (Krmnicek, 2009; cf. Kemmers and Myrberg, 2011). Such a holistic approach, considering both the materiality of coins and the symbolic character of their images, has allowed a more objective research into the production and distribution of coins, the intentions behind the choice of designs and inscriptions, and their reception by the contemporary users (Kemmers, 2009; Iossif, 2011; Noreña, 2011; de Callataÿ, 2018; Iossif, 2018b; Faucher, 2018).

1.3. Coins as an informational system

In the work presented in this thesis, coins are seen as a form of information technology, a system of culturally evolved objects combining material and symbolic characteristics, which encode and transmit information necessary for monetary exchange. Although choices made by the issuers regarding the physical and graphic properties of the coins often included intentions and meanings beyond their monetary function, and coins were used in various different contexts, here we focus on their primary role as currency.

It has been argued that money emerged as a kind of memory-keeping device, originating from the practice of recording information about transactions, credit and debt, mediating the exchange of goods and social relationships inside a community (Hart, 2005, pp. 170–1; Graeber, 2011; cf. Nelms and Maurer, 2014, p. 61 ff.). Coins, as a physical representation of money, could be seen as serving a similar informative purpose. While they are also used to mediate exchange, unlike credit and debt registers coins do not record information about individual transactions, but on their issuing authority and value. This information is necessary to allow users to recognize valid coins and use them as money (Cribb, 2009, p. 498 ff.; Kemmers and Myrberg, 2011, p. 94 ff.).

Both the material properties of coins and their graphic designs are integral parts of this informative function. From their origins as lumps of precious metal marked with stamped symbols in the ancient Mediterranean to contemporary token money, coins developed as a universal means of exchange. Once their value was determined by a political authority and certified by a stamp, coins could circulate inside the sphere of influence of that authority without the need to weigh or test them – unless fraud was suspected (MacDonald, 1905, pp. 2, 6; Seaford, 2004, pp. 120, 149). This enabled the exchange of various commodities independent of individual negotiation abilities or personal connections (Seaford, 2004, p. 9). Similar to seals and writing, which emerged in Mesopotamia several millennia before, coins are one of the revolutionary inventions which increased humanity's capacity for storing information beyond the limitations of individual or collective memory and transmitting it across time and space, which boosted the evolution of human culture from institutions and trade to arts, technology and science (Morris, 2013, p. 218 ff.; Seaford, 2004, pp. 122–124; cf. Renfrew, 1998; Avery, 2012, p. 119 ff.).

1.3.1. Information and communication

Information exchange through a conventional system of symbols forms a basis of communication. The foundations for the theory of information and communication can be found in the work of mathematicians and engineers in the Bell Laboratories. Building on the ideas of Harry Nyquist and Ralph Hartley, Claude Shannon published his *Mathematical Theory of Communication*, describing it as transmission of information in a form of message through a communication channel from a sender to a receiver (Shannon, 1948). The second publication of this work included introductory notes by Warren Weaver, who presented the main points of Shannon's work as a generalized theory of information, defining information as "a measure of freedom of choice when one selects a message" in the process of communication, not describing content of "individual messages (as the concept of meaning would)" (Shannon and Weaver, 1949, p. 9). Information is thus understood as a measure of uncertainty, or entropy, expressed as a probability of a message being selected from the pool of possible messages.

The goal of Shannon's mathematical theory was to address the technical issue of accurately encoding and decoding messages, necessary for the development of novel communication technologies, while the "semantic aspects of communication" were not relevant (Shannon and Weaver, 1949, p. 31). However, Weaver characterized this "technical problem" as the first of the "three levels of communication problems" outlined in his introduction, suggesting that information theory could be expanded to address the "semantic problem" of meaning conveyed by the symbols transmitted in communication, and the "effectiveness problem", concerning the desired effect of the communicated message on the recipient (Shannon and Weaver, 1949, p. 24 ff.). Weaver compared Shannon's "entropy" as "information" to the concept from thermodynamics known by the same name, claiming that the stochastic processes creating both kinds of entropy are equivalent (Shannon and Weaver, 1949, pp. 12–3). In physical systems, entropy is perceived as randomness, disorder in the system, which made Shannon's choice of this term to define information somewhat counterintuitive.

Independently of Shannon and Weaver, Norbert Wiener, mathematician and philosopher working on the early theory of cybernetics as "communication in animals and machines", discussed information as the negative of entropy, and thus a measure of the degree of organization within a system (Wiener, 1948; similar to the ideas of Schrödinger, 1992 [1944]; cf. Robinson and Bawden, 2014, p. 129). Wiener's theories were expanded by

Gregory Bateson, who developed a cybernetic theory of mind and communication including both artificial and biological systems. He put forward a relational view of information as an observable or measurable difference between states of being, events, objects or signals in a certain context, which, when occurring in a predictable pattern are considered to have meaning (Bateson, 1972, p. 140 ff; 162 ff.; cf. Favareau, 2009). Bateson's work on forms and patterns in linguistics, anthropology, sociology and psychology opened possibilities for applying information theory to human communication (Bateson, 1972; Brier, 2014).

Information theory based on the work of Shannon and Wiener found its application in various fields, from physics and evolutionary biology, to philosophy and social sciences (Robinson and Bawden, 2014). However, Shannon's statistical model of communication as transfer of information was challenging to adapt to the subjective view of information in social sciences, as it was not concerned with meaning and knowledge transmitted in communication (Cornelius, 2002). The semantic concept of information as the content of transmitted messages, based on Shannon's model of communication and adapted to the study of symbolic communication was first proposed by Yehoshua Bar-Hillel and Rudolf Carnap (1953). In semiotics and linguistics, the model of communication using codes, a system of conventions shared by the interlocutors, was developed by Roman Jakobson, who combined the linguistic theory of Ferdinand de Saussure with information theory and cybernetics, and it was later expanded to multiple cultural domains beyond language by Umberto Eco (Jakobson, 1960; Eco, 1979; cf. Geoghegan, 2011; Nöth, 2014). In psychology, information theory was an important factor in the emergence of cognitive science and neuroscience (Miller, 1951, 2003; MacKay, 1969). Donald MacKay further developed the concept of semantic information, focusing on the goals of communication and its effects on the recipient, where the meaning of a transmitted message depended on the social context of both involved parties (MacKay, 1969; cf. Cornelius, 2002).

In the following decades, more attention was given to the role of cognition in human communication, moving away from the mechanistic models of the brain as an information processing machine exchanging symbols, and instead developing models taking in the account the pragmatics of the conscious communication of meaning (Brookes, 1980; Belkin, 1990). Pragmatics and semantics of communication in a sociocultural context were also studied by Fred Dretske (1981), who saw information as a combination of the intended meaning of the message, and its interpretation by the recipient in a given context – meanings were subjective and had to be negotiated through communication (Cornelius, 2002).

According to Dretske, an informative message is the one that has new and meaningful content, which adds to the knowledge of the recipient through repeated exchange, as opposed to meaningless gibberish, false or repeated statements, which are not informative (Brier, 2014). Jon Barwise and John Perry studied the primary role of language in the transmission of information, and suggested that linguistic meaning arises from repeated relations between "situations" (basic units of reality) (Barwise and Perry, 1983; cf. Cornelius, 2002). Economist Fritz Machlup prioritized information as a property of the interaction between the individuals in a certain sociocultural context, which, unlike the technical concept based in Shannon's theory, does not need to add to the knowledge of the recipient (Machlup, 1983; cf. Brier, 2014).

Despite the differences between definitions of information in various disciplines, they shared a common methodological approach to quantifying information. This has eventually created a need for an interdisciplinary theory of information and communication in different types of systems. Nikklas Luhmann, under the influence of Shannon and Bateson, developed a theory of communication in social systems as a combination of utterances (form of a message), information (content of a message), and understanding (the meaning of the combination of form and content), all of which are seen as types selected out of the pool of all possible types available in the environment (the context). Selecting a type reduces the entropy, with meaning being determined by the receiver through processing the distinction between what was communicated and what was not (Luhmann, 1995; cf. Cornelius, 2002; Seidl, 2004; Brier, 2014).

Information theory, systems theory and cybernetics influenced the work of anthropologists and archaeologists in the second half of the 20th century, in particular the structuralist theory of Claude Lévi-Strauss and processualist theorists like Lewis Binford and David Clarke (Binford, 1965; Clarke, 1968; cf. Doran, 1970; Geoghegan, 2011). In his *Analytical Archaeology*, Clarke defined culture as an informational system of ideas, behaviours and artefacts, transmitted between generations inside a society and between societies (Clarke, 1968; as cited in Lycett and Shennan, 2018, p. 213). In his theory of cultural systems, artefacts played an important role, not merely as passive reflections of culture, but also as a means of transmitting cultural information, which could also be uncovered by the archaeologists analyzing the patterns of artefacts in archaeological record (Clarke, 1968; as cited in Lycett and Shennan, 2018, pp. 213, 216).

1.3.2. Cultural evolution, cognition and material culture

Recording and explaining the diversity of human cultures has been one of the central goals of both anthropology and archaeology, and different theoretical and methodological approaches were developed to systematically study the patterns of cultural change. The nature and role of signs and symbols and their meaning has always been a notoriously complicated topic in archaeology. Aiming to reconstruct the lives of ancient human societies by studying patterns in the remains of their material culture, the focus of archaeological methodology tends to be on the physical, measurable properties of the excavated material, features such as the shape and size of pots or stone tools, which are often interpreted as "functional" or "technological". Unusual, decorated, image-bearing objects or their features, whose function or meaning is not as straightforward to understand, are often labelled as "style". While "functional" elements are meant to fulfil a particular purpose, and their features are therefore constrained, the choice between different "styles" is in comparison virtually unlimited (Hegmon, 1992).

In the middle of the 20th century, Claude Lévi-Strauss developed structuralist theory in anthropology, influenced by the work of the linguist Ferdinand de Saussure, and defined culture as a dynamic communication system of interconnected units with symbolic meaning which can be understood through structural analysis (Hegmon, 1992; Terray, 2010). The influence of linguistics over structuralist theory has led archaeologists interested in the meaning of artefacts and symbols to draw strong parallels between the structure and semiotics of languages and material culture (Preucel, 2014).

This analogy was further developed by post-processual archaeologists, who emphasized the symbolic and communicative role of the "stylistic" features of human material culture. Ian Hodder proposed that meanings in material culture can be "read", making an analogy between the artefacts in a particular archaeological context and the words of a text, and proposed that objects have three kinds of meaning: one concerning the way they are used ("functionalist" or "pragmatic"), the other as a part of a symbolic system ("structural" or "symbolic"), and finally their meaning in a particular historical context ("historical meaning"), which he deems the most important (Hodder, 1991a, 1987; cf. Hays, 1993). Finding the classical structuralist view too static and detached from the reality of archaeological contexts, post-processualists argued that different meanings of artefacts are actively shaped by individual agents as means to construct and negotiate social identities

(Shanks and Tilley, 1996; cf. Hegmon, 1992). Models based on Saussurean semiotics, which presumed arbitrary relationships between signs and referents, were replaced by a broader and more flexible model proposed by Charles Sanders Peirce, which includes the observers and opens the possibility to interpret the meaning from different perspectives (Preucel and Bauer, 2001; cf. Hölscher, 2014).

Critics of the structuralist approach have argued that interpreting culture in general as a communication system analogous to language assumes that all culture is language-dependent, and does not offer appropriate causal explanations of cultural phenomena (Bloch, 1991; Sperber, 1985). Taking the "linguistic analogy" too far risks misinterpretation or over-interpretation of symbolic systems. Even when symbols are designed specifically for the purpose of representing language, as is the case with writing systems, their structure is rarely equivalent to the structure of the language that they encode.

A more analytical approach to symbolic and "stylistic" elements of culture has been taken by Martin Wobst (1977), who proposed that style does have a function as a means of information exchange. He discussed stylistic variation as a way of transmitting social information about the boundaries between different societies or between different hierarchical groups inside the same society, reopening the debate on the role of style in the communication of cultural information, which was generally dismissed by processual archaeologists, who focused on the "functional" elements of material culture (Hegmon, 1992; cf. Shennan, 1994a; Bettinger et al., 1996). Wobst's view was further developed by Margaret Conkey (1978) and Polly Wiessner (1983). Wiessner focused on the active role of stylistic elements in shaping social identities, both as signs of group affiliation or identity ("emblematic style"), or as dynamic markers of personal identity ("assertive style"). In contrast, James Sackett (1982) viewed stylistic variation as a product of a "culture-historical" context, where features would be chosen and reproduced with no specific intention ("isochrestic" variation). The debate that followed (Wiessner, 1985; Sackett, 1985; cf. Binford, 1989; Hegmon, 1992) established a consensus recognizing that the majority of stylistic variation is isochrestic, but there are cases where it becomes assertive and communicative.

In the last decades of the 20th century, the theory of cultural evolution emerged as a new approach to studying cultural change. Understanding culture as information, both present in people's minds and manifested as behaviour or artefacts, cultural evolution studies processes and underlying mechanisms shaping cultural traits over time (Mesoudi, 2011, p. 3 ff.). Grounded in Darwin's evolutionary theory of "descent with modification", it assumes certain parallels between human biological and cultural evolution, most importantly concerning the inheritance of cultural traits over generations, which can be modelled using the methods from evolutionary biology, as selection, mutation and drift (Cavalli-Sforza and Feldman, 1981). The "standard" theory of cultural evolution sees culture a set of traits which are socially transmitted between individuals or populations, and can affect their biological fitness by helping them adapt to the environment ("gene-culture coevolution" or "dual inheritance theory", see Cavalli-Sforza and Feldman, 1973; Lumsden and Wilson, 1981; Boyd and Richerson, 1985; Feldman and Laland, 1996; Richerson and Boyd, 2008). An alternative view, based on cognitive science and anthropology, proposed by Dan Sperber (1985, 1996; called "epidemiology of representations" or "cultural attraction theory"), sees culture as the set of "representations" (ideas in the mind and their manifestations in the physical world), which spread in the population through interactions between individuals. In this process, the representations are transformed, affected by individual memory and cognitive biases, and converge around a point in the space of possibilities ("factor of attraction"). The plausibility of the analogy between biological and genetic evolution and their interaction, the appropriate level of analysis, and the nature of the mechanisms of cultural transmission have been heavily debated over the years (Mesoudi et al., 2006; Eerkens and Lipo, 2007; Sperber and Claidière, 2008; Henrich et al., 2008; Aunger, 2009; Claidière et al., 2014; Lewens, 2015; Morin, 2015a, 2016; Acerbi and Mesoudi, 2015; Mesoudi, 2017; Scott-Phillips et al., 2018; for a synthesis see Sterelny, 2017).

Evolutionary thinking in archaeology has changed from its beginnings in culture history, to contemporary approaches, balancing between objectivity and subjectivity, rationality and relativism (Shennan, 1994b, 2008). Based on a modern interpretation of the Darwinian evolution of human species and culture, contemporary evolutionary archaeology differs from the 19th century concept of linear social evolution, which promoted the superiority of white Western cultures and has since been strongly rejected (Shennan, 2009a; O'Brien, 2010). In many ways, evolutionary models of the human past build on processualist research on long-term processes causing the observed variation in the archaeological assemblages, with a goal to identify and understand the underlying mechanisms behind these variations (Dunnell, 1980; O'Brien, 1996; O'Brien and Lyman, 2000; Lycett, 2015; Lycett and Shennan, 2018; cf. Renfrew and Cooke, 1979).

Robert Dunnell advocated the application of Darwinian evolutionary theory to explain variations and structure in archaeological record, while pointing out the theoretical and methodological differences between biological and cultural evolution, stemming from the fact that culture is not transmitted genetically (Dunnell, 1980). Conversely, he argued that although the transmission of some cultural traits is guided by natural selection, and these traits are retained because they increase the adaptive fitness of the humans that adopted them (culture being a sort of an "extrasomatic adaptive system", cf. Binford, 1965), not all cultural traits are adaptive, and the transmission of such traits does not depend upon natural selection, but a neutral process of random sampling from the pool of existing variants, similar to genetic drift (Dunnell, 1978). Applied to material culture, Dunnell suggested that technological, "functional" properties of artefacts are selected for, as they "directly affect the Darwinian fitness of the populations in which they occur", whereas non-functional traits ("style"), "do not have detectable selective values", and the patterns of variation in these kinds of traits are a result of "non-evolutionary, stochastic processes" (Dunnell, 1978, p. 199).

Dunnell's "natural selection" was not equivalent to the biological process operating over human genes, but seen as an analogous evolutionary mechanism operating over cultural variants, artefacts or archaeological features (e.g., architecture, pits or ditches) as units of selection, increasing the frequency of more adaptive traits in the next generation. Later renamed as "cultural selection", this mechanism was seen as a dominant evolutionary force shaping the cultural evolution of human populations (O'Brien and Holland, 1990, 1992; Lyman and O'Brien, 2003). However, the transmission of many cultural traits is affected by mechanisms other than selection, which cannot be explained only in terms of either adaptation or random variation, as proposed by Dunnell (Bettinger et al., 1996). Research on cultural evolution has since focused more closely on identifying different mechanisms of cultural transmission between generations and among individuals and groups in a population (Maschner and Mithen, 1996; Shennan, 2009a).

Grounded in the functionalist view of culture as an adaptation to environmental conditions, the approach to cultural transmission building on the dual inheritance theory of Boyd and Richerson also considered the role of different social and cognitive factors (biases) influencing an individual's choice of cultural variants in the process of social learning, in addition to individual experimentation (Bettinger et al., 1996; Eerkens and Lipo, 2007; Henrich, 2001; Mesoudi and O'Brien, 2008; O'Brien, 2008). Apart from directional change, patterns in cultural variants can also emerge as a result of neutral processes, for instance certain traits are inherited in a "package" of correlated variants, and others simply because they were more prevalent in the previous generation (Bettinger et al., 1996). The research on neutral processes of cultural change was expanded beyond the concept of "style" to include cultural traits such as personal names or dog breeds, and demonstrated that discriminating between different evolutionary mechanisms influencing the patterns in the historical data is far from straightforward (Neiman, 1995; Bentley et al., 2004; Kandler and Shennan, 2013; Lipo and Madsen, 2001; cf. Hurt and Rakita, 2001).

Most of the empirical research in cultural evolution has been concerned with the development of mathematical models of cultural transmission. Successful application of phylogenetic models of vertical inheritance (from the previous generation to the next) has expanded the possibilities of research on the long-term evolution of cultural lineages of various artefacts, e.g., stone tools (Bettinger and Eerkens, 1999; O'Brien et al., 2001), pottery (Collard and Shennan, 2000) and textiles (Tehrani and Collard, 2002; see also contributions in Lipo, et al. 2017). However, these macroevolutionary models have been criticized by some anthropologists and archaeologists, concerned that the generalizations are glossing over the cognitive background of decision making and behavioural patterns of individual agents (Shennan, 1993; Sperber, 1996; Shennan, 2008; Colleran and Mace, 2011; cf. Gray and Watts, 2017). These discussions have shaped the contemporary applications of cultural evolutionary theories in archaeology. The fragmentary nature of the archaeological record made it necessary to focus on "micro" patterns caused by individual interactions in a particular historical context, and on their role in shaping the "macro" processes by applying mathematical models, deepening the inquiry of interactions between environment, genetics, cognition and culture in shaping the human past (Maschner, 1996; Shennan, 2009b; Prentiss, 2019). The integration of an evolutionary framework in archaeological research has helped formalize inquiries into the mechanisms of diachronic change and stability of human culture, and it has also provided the field of cultural evolution with the opportunity to test its hypotheses on "real-world" data (Shennan, 2011).

The interaction of cognition and culture in shaping human evolution has been a focus of studies on the emergence of symbolic communication, from prehistoric engravings and medieval heraldry to writing, numerical notation and language (d'Errico, 1998; Tylén et al., 2020; Chrisomalis, 2018; Morin et al., 2018; Morin, 2018; Morin and Miton, 2018; Miton and Morin, 2019; cf. Colagè and d'Errico, 2020; Sterelny, 2020). Evolutionary cognitive archaeology, the field influenced by the research on the origins and development of human cognition in evolutionary psychology, sees the evolution of the human ability to make marks, attribute meaning to them, and use them in intentional communication, as a consequence of the integration and generalization of "mental modules", cognitive mechanisms evolved to tackle specific tasks or process certain kind of information (Mithen, 1995, 1996; Renfrew, 1998; Mithen, 1998; for an overview see Abramiuk, 2019).

Comparative and experimental studies in cognitive psychology and linguistics have expanded our knowledge on the origins of language and communication systems (cf. a recent review of the field by Nölle et al., 2020). Experimental studies of artificial languages emerging *de novo* in the laboratory through transmission have demonstrated that structured communication systems evolve through social interaction between individuals (Kirby et al., 2008; Galantucci et al., 2012). Research on graphic communication shows that emerging sign systems display similar properties as languages, such as simplification through refinement from iconic sings (resembling their referent) to arbitrary symbols, compositionality (combining signs to create new meanings), and grammaticalization (signs losing their meaning and being retained as structural markers) (Fay et al., 2018, 2014; Garrod et al., 2007). This similarity does not imply that graphic sign systems are necessarily language-dependent, nor that they are structured in the same way as languages, but it highlights the similarity of the cognitive mechanisms underlying human communication, regardless of its form. Similarly, looking at culture broadly as "information", and cultural transmission as a type of communication, does not presume it to be linguistic in character.

1.4. Quantifying information

The work conducted in this thesis has mainly relied on the use of information theoretic measures and quantitative analysis of data collected from publicly available numismatic databases, catalogues, or additional online resources. An important consideration throughout this doctoral project has been the application of principles of open science (Bezjak et al., 2018). In an attempt to make this research openly available and reproducible, all empirical hypotheses and predictions have been preregistered on the Open Science Framework, where the data and code used for analysis and testing were also subsequently published. The need for open and reproducible research is often discussed in social sciences and digital humanities, but it is becoming increasingly important in archaeology as well (Marwick, 2017).

Studies reported in Chapters 2 and 3 investigated the structure of ancient Greek coins and the changes in the amount of information contained specifically in graphic designs. They were both based on an extensive dataset of over six thousand unique types of ancient coins predominantly produced by Greek polities all over the ancient Mediterranean, compiled from two digital collections, the *Sylloge Nummorum Graecorum* database and the *MANTIS* database of the American Numismatic Society (Carradice and Popescu, n.d.; American Numismatic Society, 2015). Although it was collected from trustworthy sources, the data required a lot of automatic and manual cleaning and reformatting to make it suitable for quantitative analyses (see Appendix 1). The most important changes included transforming the descriptions of coin designs into strings of standardized motifs, and standardizing the names of authorities and denominations according to pre-established guidelines (see section 0.4 in Appendix 1, section 2.3 in Chapter 2 and section 3.2.3 in Chapter 3). The focus on designs, unique combinations of obverse and reverse image types, rather than on individual motifs, was motivated by the fact that the majority of motifs in our sample appear only on a small number of coins (less than ten), and their informational value outside the context of designs is mostly too small to be relevant.

In order to quantify the information present in designs, we used measures based on information theory (Shannon and Weaver, 1949; Wiener, 1948). Called "mathematical theory of communication" by its originators, it provides a way to measure the amount of information in a variable by quantifying uncertainty (entropy) based on the probability of possible outcomes (e.g., random coin tosses, dice rolls, or messages produced by a telegraph machine). The smaller the number of possible outcomes, the lower the entropy, and the more information the variable contains. Additional measures, such as conditional entropy and mutual information, can be used to assess the relationship between two variables. Measures based on information theory have been used in language research, e.g., to operationalize the "meaning" assigned to symbols in artificial language experiments (Winters et al., 2015; Kanwal et al., 2017; Winters and Morin, 2019), to understand language structure (Piantadosi et al., 2011; Ferrer-i-Cancho and Martín, 2011; Pimentel et al., 2019) or to assess mutual intelligibility of different languages (Moberg et al., 2007). They have also been used to study the structure of various symbolic systems, e.g., as an aid in distinguishing writing systems from non-linguistic symbol systems (Sproat, 2014), to track the cultural transmission of rock art (Caridi and Scheinsohn, 2016), reconstruct ancient texts from different manuscripts (Cisne et al., 2010), or study the increasing complexity of paintings through history (Sigaki et al., 2018). However, they have never been applied to measure the informational value of coin properties.

The study presented in Chapter 4 investigated the representation of monetary value in the physical and graphic properties of contemporary coins. It involved constructing a comprehensive dataset of coined denominations issued for contemporary currencies. The data were gathered from official documents published by the respective monetary authorities and from collectors' manuals. The focus of this study was on the information that allows users to tell apart coins of different value, rather than on measuring informational value of a particular property. In an informative system of coined currency, the difference between the properties of neighbouring denominations was expected to correspond to their difference in value. Therefore, in this study information was quantified not in terms of information entropy, but as differences in diameters, designs and colours between the coins of neighbouring value belonging to the same currency (e.g., a 1 euro coin and a 2 euro coin). While the difference between diameters could be measured directly, differences in designs and colours between denominations were assessed by two independent coders (see sections 1.4 and 1.5 in Appendix 2). The reliability of coding was checked by quantifying the agreement between the two coders, which helped to eliminate human error in the data.

Studying symbolic systems, including image-bearing artefacts such as coins, from the perspective of information theory allows us to uncover the underlying mechanisms and the role of cognition and culture in their emergence and use. Instead of focusing on meaning, which depends on a particular sociocultural context that is often missing for historical objects, information theory provides us with methods to reconstruct the lost information from their structure and distribution in the archaeological record.

1.5. Overview of the chapters

The main part of this thesis consists of three chapters, two of which are published as articles in peer-reviewed journals, with the third being submitted to one.

Chapter 2 focuses on ancient coins from their invention in the late 7th century BCE on the Ionian coast of Asia Minor, until the end of the 1st century BCE, when the Romans established their rule in the eastern Mediterranean. Coins played an important role in the gradual political consolidation of the Hellenic world, from city-states to federations and Hellenistic empires, and in the economic growth that was stimulated by the rise of markets and monetized trade. In turn, these changes shaped coins in early stages of their evolution. Starting from this assumption, the first study investigates the influence of changing political and economic circumstances on the emergence and evolution of coinage, in particular their graphic designs as indicators of their issuing authority and monetary value.

Although the repertoire of images minted on the coins of ancient Greek polities was impressively variable, designs were also imitated for various political, economic or aesthetic reasons, and shared by the members of political alliances and monetary unions. With time, this would result in less distinctive designs, whose informational value as symbols of a particular authority would be eroded, making them more ambiguous. On the other hand, in the context of intensified monetary exchanges between different polities, it would be practical to mark different denominations with different designs.

Using information theoretic measures, the amount of information in coin designs was quantified as distinctive correspondences between the unique designs and the issuing authorities or denominations produced in a certain period. The analyses show that coin designs with time lost their informational value as marks of authority, but gained increasing amounts of information about the denominations. The difference between the informational content of higher and lower denominations suggests that coin designs have been carefully designed in order to communicate value to the users. This last point has been further examined in the research conducted on modern coins presented in Chapter 4.

Chapter 3 discusses the methodological implications of quantitative approaches to coin iconography, with a broader discussion of the opportunities and challenges brought about by digitization and data standardization in the humanities and social sciences.

In order to check whether the coding decisions made in the process of constructing the dataset for the study presented in Chapter 2 influenced the outcomes of our statistical measures and analyses, design descriptions were recoded according to different criteria, resulting in either very generalized or very detailed strings of motifs. In the case of this particular study, the information theoretic measure we used showed to be robust to these changes in granularity of designs coding. However, there is a case to be made in favour of generalized standards for coding iconographic data, focusing on basic concepts, limiting the level of detail and keeping the coding simple, thus increasing the interoperability of the dataset, and making it easier to share and integrate with other datasets.

Despite the increasing number of digital collections of cultural data, the available standardized formats do not resolve the particular challenges of accurately representing and coding visual culture. This study argues in favour of developing flexible yet consistent standards, which would enable quantitative research necessary for proper contextualization and interpretation of images.

Chapter 4 examines how different coin properties represent monetary value, and how this value is perceived by users, with important implications for understanding the evolution of coins, their origins, uses, and function in various historical contexts.

The study was conducted using a dataset of contemporary coins, as they represent the most recent stage in the evolution of coined money. Modern coins are true token money: their value as a commodity is far below their exchange value, set by the monetary authority. This means that their physical properties, such as size, weight, thickness, metal and colour are chosen arbitrarily, and this is also true of their graphic designs. However, for coins to be a successful medium of exchange, they should efficiently indicate the value they represent.

Because modern denominations, similarly to their ancient predecessors, are arranged in such a way that the differences in value between the neighbouring denominations increase exponentially, these differences should be indicated by similarly distinctive coin properties, thus avoiding the risk of confusing the coins. This hypothesis was confirmed for graphic designs and colours, but not for sizes. Differences in design and colour between coins of neighbouring value denote distinct denominations, marking greater differences in values more saliently. On the other hand, coin sizes are found to be a good indicator of their absolute value: larger coins are on average also more valuable, regardless of their relative position in the currency. Interestingly, the relationship between values and coin properties is shown to be logarithmic in shape, in line with the proposed model of the way humans process numerical quantities.

Each chapter includes a statement of author contributions. The final chapter provides a general discussion.

2. The evolution of information in ancient coin designs

2.1. Author contributions

This chapter has been published as an article in the *Journal of Anthropological Archaeology* in December 2019 (https://doi.org/10.1016/j.jaa.2019.101103). The study has been preregistered on the Open Science Framework (see Appendix 1), and conducted by Barbara Pavlek under the supervision of Olivier Morin in collaboration with James Winters, in the Minds and Traditions research group (The Mint) at the Max Planck Institute for the Science of Human History in Jena (MPI-SHH). The study concept was conceived in collaboration of all three authors. Data were collected and curated by Barbara Pavlek, who also carried out data analyses with help from the co-authors. All three authors have contributed to the writing of the manuscript.

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The code and data are available in the online repository at:
http://osf.io/tkv67/?view_only=65bc6dbcc69c49308491598a95f15c6b.

2.2. Pavlek, Winters, Morin (2019). Ancient coin designs encoded increasing amounts of economic information over centuries

2.2.1. 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, 2018a). 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 monetized economies as political innovations alien to traditional exchange systems (Bohannan, 1955; Polanyi, 2001 [1944]). If, on the other hand, coins stand for units of value whose utility derives in large part from decentralized market exchanges that may exist independently of state authorities, this authorizes a view of monetary exchanges as in some ways continuous 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, 2001 [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.).

2.2.2. 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. 7–9; 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.

2.2.3. 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 (Figure 2.1). 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.

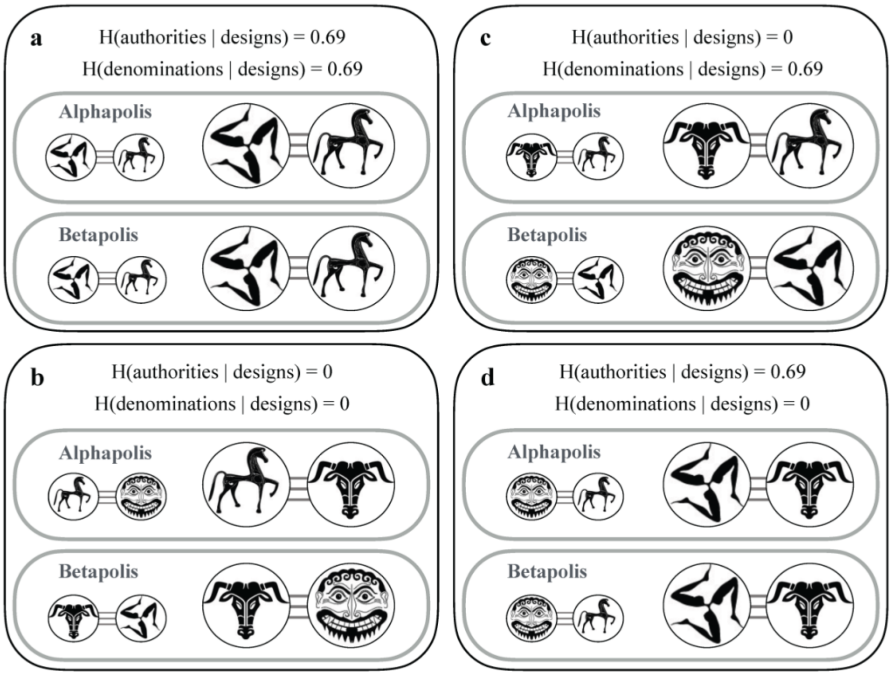

Figure 2.1. Conditional entropy measures the amount of information that coin designs carry about their issuing authority or denomination. Two city-states, Alphapolis and Betapolis, issue two different coins, one for each denomination: the "small coin" and the "large coin". When all four coin designs 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).

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):

(1)

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

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 ∈ A and b ∈ 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):

(2)

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

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).

2.2.4. 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 constituted by

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.

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.

2.2.5. 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) (Figure 2.2.)

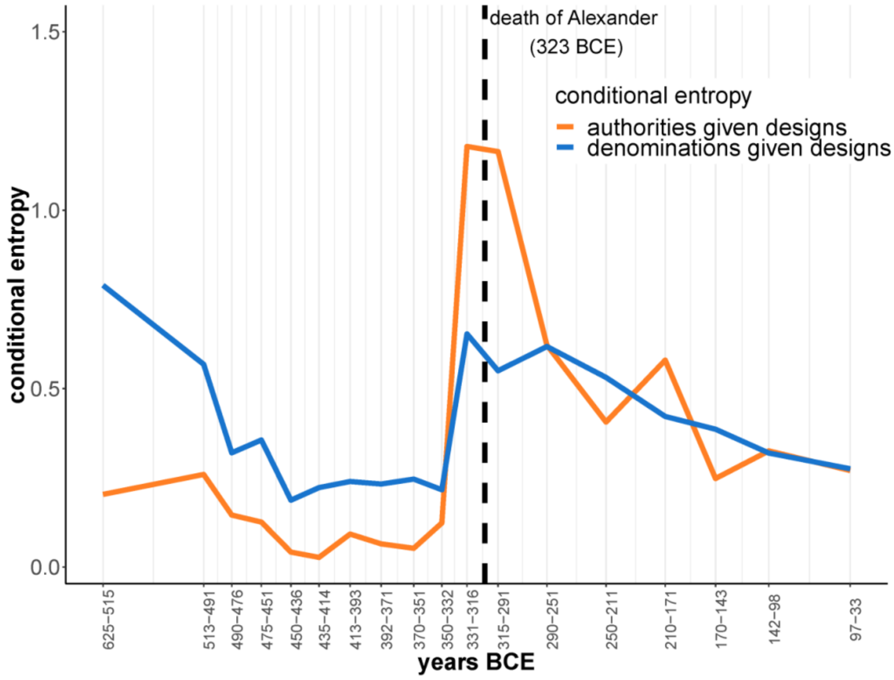

Figure 2.2. The evolution of state-relevant information and value-relevant information in ancient Greek coins (c. 625–c.33 BCE). The state-relevant information carried by coin designs (orange line) is indicated by the conditional entropy of the coins' issuing authorities given their designs, and value-relevant 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.

The rise of Macedon, starting with Philip II's victory in the Battle of Chaeronea in 338 BCE and continuing with 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 (Figure 2.3). 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 (AICnull = 485 vs. AICtest = 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 (AICnull = 496 vs. AICtest = 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.

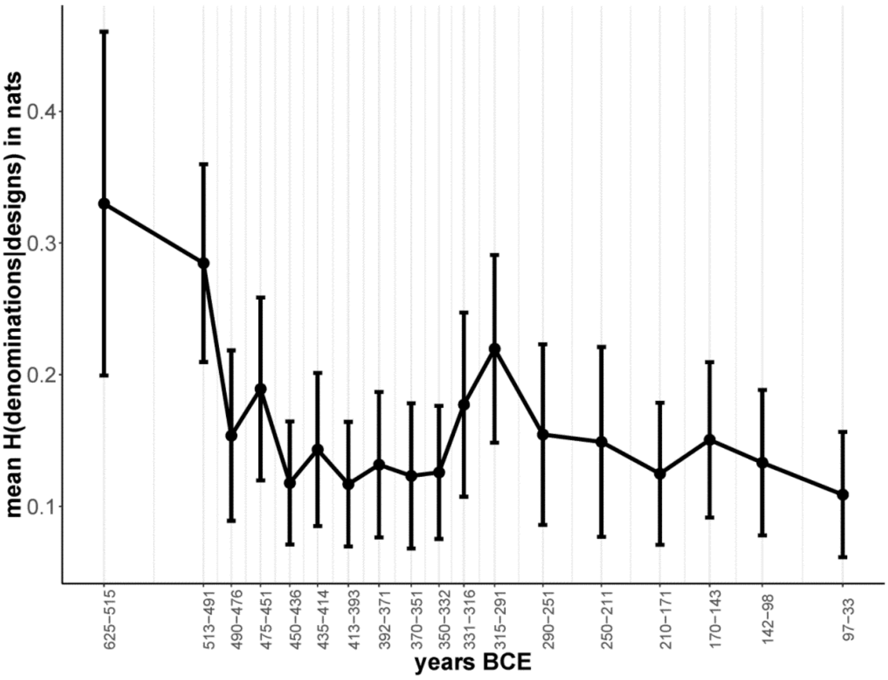

Figure 2.3. The evolution of the value-relevant information carried by ancient Greek coins, on average, across distinct states (c. 625–c.33 BCE). Value-relevant information was computed as the conditional entropy of denominations given designs (in nats), on the y-axis. High entropy indicates low information. 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.

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 (AICnull = 2375.3 vs. AICtest = 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 Figure 2.4). Having divided our corpus into two subsets, high- and low-value coins, we sub-divided 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 ($W = 30.5$; $p = 0.0334$). We can therefore rule out the possibility that high-value coins contain more value-relevant information because they bear a larger number of motifs.

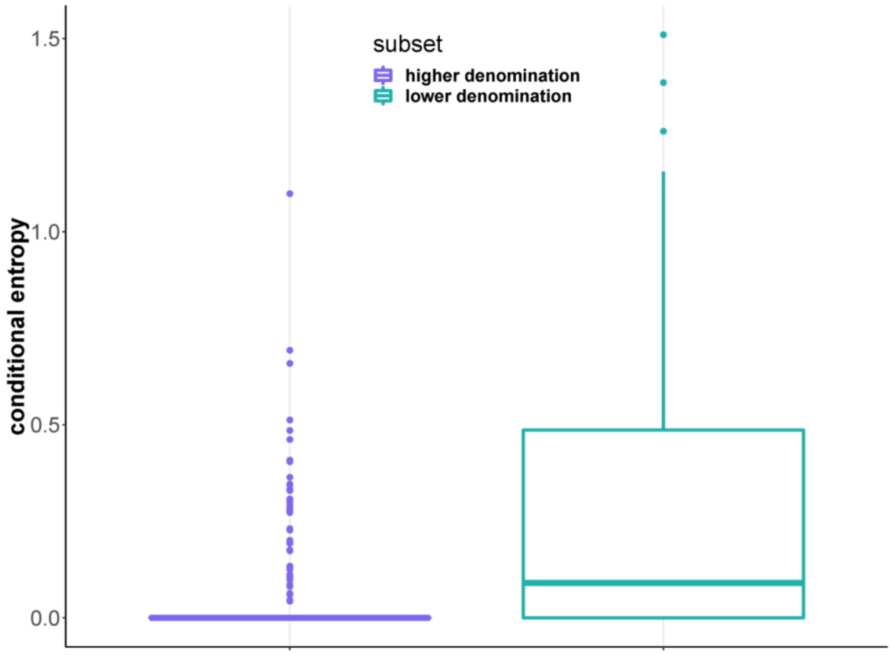

Figure 2.4. The value-relevant information carried by the designs of the low-value and high-value coins issued by 353 authorities. Value-relevant information was measured as the conditional entropy of the coins' denominations given their designs (on the y-axis, in nats). High-denomination coin types (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

2.2.6. 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. 7–9; 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; Rutter, 1983). 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

2.3. Additional analysis

While preparing the data for additional analyses presented in Chapter 3, we detected some mistakes inherited from the source datasets, which went unnoticed in the original study (Chapter 2). These included 120 coins attributed to wrong authorities (of which four also had a wrong date), 57 with wrong denominations, and 48 with incomplete or incorrect design descriptions. These mistakes were corrected, and the numerical codes for authorities, denominations and designs have been updated (Pavlek et al., 2019; see Suppl. Mat. section 0.4). We excluded 67 coins with problematic authenticity (57) or damaged designs (10). At the end, we have excluded 24 duplicated coins (sharing the same date, authority, denomination and design). The final dataset consisted of 6768 unique coin types, issued by 594 unique authorities, in 136 unique denominations and with 3281unique design types. The summary of interventions per data source is given in Table 2.1 below. Most of these issues are resolved in the most recent version of the *MANTIS* database, while the same is not the case with the *SNG* dataset, which does not seem to have been recently updated.

INTERVENTION	SNG	MANTIS	TOTAL
corrected authority	55	65	120
corrected denomination	1	56	57
corrected obverse/reverse description, recoded design	6	42	48
corrected date	2	2	4
removed (problematic)	3	64	67

Table 2.1. Summary of interventions to the original dataset, by source and in total. Of 6859 original coin types, 1511 were obtained from the *SNG* database, and 5348 from the *MANTIS* database.

After these revisions, we repeated the analyses conducted in Pavlek et al. 2019 (Chapter 2, see section 2.2.5) on the corrected dataset. The changes did not affect the main results of the original study in a meaningful way. We still see the decrease in authority-relevant information with time ($\rho = 0.554$, $p = 0.019$ for the normalized entropy of authorities given designs through 18 time bins). The amount of denomination-relevant information increases with time, both in general terms ($\rho = 0.178$, $p = 0.477$ for the normalized conditional entropy of denominations given designs through 18 time bins), and when taking in account the variation between the issuing authorities (β -0.0002, $t = -2.48$, AICnull (500) > AICtest (496) for the normalized conditional entropy of denominations given designs over 1449 time-authority bins). The designs still do not seem to get more organized with time ($\rho = -0.218$, p

= 0.384), and the higher denominations tend to have more informative designs, if grouped by their issuing authorities (W = 19486, $p < 0.0001$ for normalized conditional entropy), but not when considering number of motifs forming the designs (W = 30.5, p = 0.0534 for normalized conditional entropy). The robustness of our original results after these corrections provided a baseline for the subsequent research conducted in the follow-up study presented in Chapter 3.

3. Standards and quantification of coin iconography: Possibilities and challenges

3.1. Author contributions

The following chapter has been submitted as an article to *Digital Scholarship in the Humanities* on 29 July 2020. As it is presenting additional analyses following directly from the previously published paper, these analyses have not been preregistered. The data were prepared and analyzed by Barbara Pavlek under the supervision of Olivier Morin and James Winters (The Mint, MPI-SHH). The manuscript was written primarily by Barbara Pavlek, with contributions from the co-authors.

The authors thank Julia Bespamyatnykh for her help in manual data coding, and Oleg Sobchuk for helpful discussions.

The data are available at:
https://osf.io/gd4mv/?view_only=c1d21aa0ebf848e78a6b65f44ca33f3a.

3.2. Pavlek, Winters, Morin (submitted). Standards and quantification of coin iconography: Possibilities and challenges

3.2.1. Introduction

In recent years, the scope and volume of research on human history has been expanded by the advancements in information technology, which allowed the creation of large online databases of cultural data, from digital libraries to interactive virtual museum collections, preserving cultural heritage and making it broadly available. A rapidly growing field of digital humanities has been developing computational approaches for data management and analysis. This digital revolution has created new possibilities for research, but it has also opened new questions and challenged traditional methods and practices. The existing systems of knowledge organization in humanities, such as terminologies and typologies, are not always consistent, nor commonly accepted, which complicates the process of digitization and the potential for cross-disciplinary collaboration. Moving resources and research to the digital domain requires rethinking classification systems, and transforming cultural data to be suitable for computational approaches.

In this paper, we discuss the importance of data standardization for the advancement of research in the humanities. We first give a brief overview of the current trends in managing digital collections of cultural heritage, especially that of classical antiquity, and discuss the issues concerning the development of standards for describing iconography, focusing on ancient coins. Here we will present different approaches to coin images, including recent examples of using quantitative methods to study their meaning, and attempts at creating standards to describe and classify them. On the example of our recent study investigating the informational value of images on Ancient Greek coins, we discuss the challenges of choosing the appropriate level of detail to keep standards useful, but simple, and illustrate the importance of reliable, standardized data as a prerequisite for a successful implementation of statistical measures.

The Linked Open Data (LOD) principles of the Semantic Web (Berners-Lee, 2006) provided a framework for data standardization and organization using ontologies, formally defined sets of key terms and concepts marked by unique identifiers, connected with semantic links. Adopting this systematic way of describing, managing and storing data enabled cross-disciplinary collaborations and data sharing between the researchers in different disciplines of the humanities (Binding and Tudhope, 2016; Huvila, 2019). The CIDOC Conceptual Reference Model, developed by the International Council of Museums, first offered a general framework to represent cultural heritage (*CIDOC*, n.d.). This standard was further developed by international collaborative projects such as CLAROS (Kurtz et al., 2009), Europeana (Doerr et al., 2010; *Europeana*, n.d.), and ARIADNE (n.d.), which support digitization and integration of collections of diverse data types: books, manuscripts, music, art, and archaeological artefacts.

General standards and mediating platforms provide essential technical and logistic support for creating domain-specific standards. Early on, scholars of the Ancient World have recognized the potential of standardized data formats for organizing digital cultural data, and adapted them to fit the needs of their own research (Elliott et al., 2014). These efforts have mostly focused on developing guidelines and tools for editing corpora of literary sources (*Perseus Digital Library*, n.d.; Smith et al., 2000), epigraphic documents (Elliott et al., 2006; Liuzzo, 2014) and prosopographies (Bodard et al., 2017) of Greco-Roman antiquity. Recently, specialists studying material culture joined this initiative, creating standardized concepts and ontologies for organizing digital collections of coins (*Nomisma.org*, n.d.; Gruber et al., 2013) and pottery (*Kerameikos.org*, n.d.; Gruber and Smith, 2015). The

Pelagios project (*Pelagios Network*, n.d.; Barker et al., 2016) provided a common platform integrating different resources through standardized identifiers for annotating ancient places. However, despite rich online collections of artefacts bearing figurative representations (e.g., *Arachne*, n.d.; Classical Art Research Centre, n.d.; Bibliothèque nationale de France, n.d.; British Museum, n.d.), there is currently no standardized approach for encoding ancient images. A popular tool for analyzing mythological depictions in ancient art, the *Lexicon Iconographicum Mythologiae Classicae*, is available online as a database of records on ancient artefacts and the associated bibliography (*LIMC France*, n.d.), but its potential as a semantic knowledge organization system has not been fully explored.

Historical artefacts are often fragmented and their original context is not always known, which makes them challenging to study. The research on ancient art has thus been mostly oriented towards description and interpretation of individual examples or groups of artefacts, rather than conducting large-scale studies seeking general trends. However, the availability of digital art collections has renewed the interest in iconography, a discipline of art history focusing on the content of images (subject matter), aiming to classify them and interpret their meaning (Panofsky, 1939; cf. Müller, 2011). Some systematically organized collections of iconographic material established since the beginning of the 20th century are partially digitized and available online (e.g., *The Index of Medieval Art*, n.d.; Warburg Institute, n.d.). *Iconclass*, the first collection-independent classification system for iconographic data, developed by Henri van de Waal in the Netherlands (published in print 1973-1985), has been recently converted to a semantic ontology format (*Iconclass*, 2009). The Getty Research Institute (2018) developed several standardized vocabulary lists to support the linked databases of cultural data, including a thesaurus of iconographic terms. There were also initiatives to expand the CIDOC-CRM ontology to include domain-specific concepts for annotating iconographic material (Dentamaro et al., 2007; Carboni and de Luca, 2019). The advancement of image manipulation and recognition technologies has inspired the debates on the future of art history in the digital age, discussing the potential of standardized semantic ontologies for supporting traditional qualitative approaches, as well as developing quantitative methods to study visual culture (David, 2015; Lozano, 2017; Gartner, 2019). Despite the challenges posed by the ambiguous character of visual culture, using standardized systems to describe and organize images would not only help manage the growing body of data, but also support the application of different methodologies testing novel research questions.

Quantitative research, providing the ability to study large-scale diachronic patterns in culture, is gaining popularity among researchers in the humanities and social sciences. Well-curated, standardized databases enabled such research on languages (List et al., 2017; Forkel et al., 2018), religion (Slingerland and Sullivan, 2017; Watts et al., 2018), folktales (Tehrani, 2013; Berezkin, 2015), literature (Hughes et al., 2012; Yucesoy et al., 2018), paintings (Sigaki et al., 2018), music (Klimek et al., 2019; Youngblood, 2019), and films (Sobchuk and Tinits, 2020). Quantitative methods are useful for modelling and statistical hypothesis testing using big, consistent and systematically organized datasets, containing information in the form of measurements or discrete observations (on different types of quantitative research, see Morin, 2015b). These observations usually come from small-scale, qualitative studies, focusing on interpreting specific phenomena. The choice of the appropriate method depends on the scope, the research question, and the nature of the data used in a study. It is therefore important to keep in mind the requirements of a particular approach when considering the design and possible applications of digital corpora and data standards (cf. Roberts and Winters, 2013).

Coins present a particularly interesting case in the context of computational approaches to historical artefacts. Combining carefully designed physical features, inscriptions and graphic representations, coins convey economic, political, and cultural information. While their potential as a rich historical source made them a well-suited candidate for digitization, quantification, and creation of domain-specific standards, finding a suitable approach to standardize coin images proves to be a rather challenging task.

3.2.2. Coin images in the context of the digital revolution in numismatics

Coins emerged in at least two independent locations. Most of the coins used in the world today are stemming from a Greco-Lydian invention at the end of the 7^{th} century BCE. The coins produced throughout the ancient Mediterranean world were marked with images that identified them as a valid means of exchange and store of value, issued by a certain authority. As a contrast, another independent tradition of metal coinage, which emerged in 5^{th} century BCE China, produced coins marked only with inscriptions (Scheidel, 2008). Figurative images are present on the earliest known coins found at the Artemision at Ephesos (Karwiese, 1991; Kerschner and Konuk, 2020). The early coins usually featured images only on one side, while the other was either blank, or included a punch mark bearing a geometric design. However, the designs composed of figurative motifs were soon present on both sides of the coin (obverse and reverse types), depicting deities, mythological figures and creatures, animals, plants and objects, sometimes even visual puns alluding to the city's name (Head, 1911, p. lv ff. Kraay, 1976, p. 2 ff.). By the beginning of the 5th century BCE most of the coin-producing city-states started minted certain images consistently, thus allowing users to recognize the authority that guaranteed their authenticity and value. Despite some images being shared by multiple authorities, the existence of stable, "diagnostic" design types, mainly associated with a single authority, has allowed numismatists to use these images to classify and date the coins (Weir, 2010).

Over the last couple of decades, numismatic research has been profiting from the creation of large online databases. The *Nomisma* project, a collaborative international initiative hosted by the American Numismatic Society, developed a structured scheme for the digital representation of numismatic data, together with a general ontology built upon the existing classification systems, providing concepts to describe relevant numismatic categories (Gruber, 2010, 2019). *Nomisma* is envisioned as a mediating platform, connecting databases covering different periods and different kinds of numismatic data (single finds or coin hoards from archaeological contexts, museum collections, auction catalogues), and making them openly available (Gruber et al., 2013). Using linked data standards helps to create machine and human readable data, allows integration of numismatic data with other material, and offers options for quantitative research using semantic queries (Heath, 2018). The *Nomisma* ontology strives to offer a sufficient number of key concepts to adequately describe numismatic data, identify and harmonize the inconsistencies between different data sources, while balancing the level of detail to fit the varied needs of its users (Tolle et al., 2018).

At the moment, data standardization led by the Nomisma project is focused mainly on the technical aspects of coins, their condition, physical properties (size, weight, metal), denomination, authority, provenance and date (*Nomisma IDs*, n.d.). As of yet, there are no standardized options for detailed annotation of obverse and reverse design types. The images are usually described in free text format, using traditional specialist terminology referring to the place of a motif on a coin (e.g., "to r. / l. of…", "in field", "in exergue"), in a way that resembles the shorthand of heraldic blazons, although it is far less standardized. Despite the typology of ancient coins being relatively well established though several generations of reference works, there is still a considerable lack of consensus on how to describe coin images and define individual motifs. In addition, most digital databases largely rely on human coders for data entry – often a heterogeneous group of collection curators, specialists and interns, with a variable level of quality control and error management (Gruber et al., 2013; Tolle and Wigg-Wolf, 2015). These issues are not limited to numismatics, but shared with other disciplines working with material culture.

For the most part, any confusion can be mitigated by accompanying the description with a photograph of the object itself and linking it to standard reference works and printed catalogues. However, due to the variable availability and format of data sources, the transformation of reference works into referential databases is for the most part still ongoing (García et al., 2019). Despite the huge progress in making numismatic data available and partially standardized, which has increased the possibilities to conduct large-scale quantitative studies concerning coin production and circulation, any attempt to conduct similar research on images would likely be constrained by the raw format of descriptions and require a substantial amount of preparatory work.

A notable step towards the standardization of coin images has been made as a part of the ongoing *Lexicon Iconographicum Numismaticae* (*LIN*) project coordinated by Maria Caccamo Caltabiano. Their goal is to develop 'an objective and scientific method for interpreting coin types' based on a structural analysis of motifs, hoping to understand the visual "language" of coins, considered to be analogous to spoken or written language (Caccamo Caltabiano, 2018, pp. 77–78). An important contribution of this project is an online database of ancient coin iconography (*DIANA*), based on the previously published indices (Caccamo Caltabiano, 2007). At present, the database includes 938 Greek and Roman coins, their motifs organized in a hierarchy of four macro-categories (person, animal/monster, flora, and object) with numerous sub-categories (posture, sex, age, clothing, attributes). The metadata give information on the provenance, value and date of each coin, allowing the users to explore the distribution of motifs and their combinations through time and space (Caccamo Caltabiano et al., 2013; Celesti et al., 2017). Still under development, this database is mainly used by the researchers associated with the *LIN* project for case studies focused on specific motifs and their assumed semantic links, trying to interpret the observed diachronic patterns of use of these images by different ancient mints (Puglisi, 2014; Sapienza, 2017). While undoubtedly useful for information organization, the explanatory power of their semantic approach has been criticized (de Callataÿ, 2018).

The potential of comprehensive coding of iconographic elements pioneered by the *DIANA* database was further developed through the cooperation between the computer scientists from the Big Data Lab at the Goethe University in Frankfurt and numismatists working on the ongoing *Corpus Nummorum Thracorum* (*CNT*) project based in Berlin (2014-2020*)*. In a recent paper, Patricia Klinger and colleagues address the disadvantages of using unstandardized free text descriptions to represent coin iconography in digital databases, which reduces the querying options to simple keyword searches (Klinger et al., 2018). Using the *CNT* Greek Coins data, they devised an NLP-based semi-automatic process to convert obverse and reverse descriptions to a machine-readable format compatible with the linked data principles. Applying machine-learning algorithms makes this approach less reliant on manual interventions, while still allowing expert supervision. It has a lot of potential to be used on different numismatic collections and applied to other types of image-bearing objects such as pottery and seals, as an important step towards creating standardized typologies.

Another line of ongoing research is employing automatic image recognition technology, aiming to develop techniques for computer-aided image-based classification of ancient coins. The goal is to help increase the accuracy and speed of primary data processing, expand the research potential of numismatic material, and aid cultural heritage management efforts in combatting illegal coin trade (Zaharieva et al., 2007; Jarrett et al., 2012; Cooper and Arandjelović, 2020). Despite the still limited practical success of this method, in their computational approach to coin images, these studies are among the few that consider the information contained in the images in quantitative, mathematical terms, emphasizing the overall structure of images and their regularities, rather than idiosyncrasies.

Numismatists have early recognized the usefulness of statistics for studying the ever-increasing collections of coins and inferring patterns in their sizes, weights, denominations and iconography, attempting to reconstruct ancient monetary systems and economies (Doyen, 2011; de Callataÿ, 2011). Images are instrumental for detecting individual types in a coin series (characterized by a unique combination of obverse and reverse dies), and estimating the total number of coins produced by an issuing authority in a given period. Quantitative methods have recently been used to study images themselves, in an attempt to understand the intentions behind the choice of certain motifs and their meaning (Faucher, 2018; Iossif, 2018b). Instead of discussing the characteristics of a small number of well-known examples, quantitative approaches provide an opportunity to study the images in the context of all known examples, thus avoiding giving undue importance to potentially exceptional objects (Iossif, 2011; de Callataÿ, 2018). However, these studies are still limited by the affordances of the database queries, and the lack of reliable coin typologies.

In our recent study, we took a different approach to images on coins produced in the ancient Mediterranean states until the end of the Hellenistic period. We quantified the amount of information concerning the issuing authorities and the economic value present in the coin images ("designs") using measures based on information theory (Pavlek et al., 2019). This allowed us to investigate the influence of political and economic circumstances of the increasingly interconnected world of the ancient Mediterranean on the amount of information stored in coin designs. We were interested in Greek and other pre-Roman coins because they represent the first examples of coined money carrying graphic designs. Unfortunately, a comprehensive dataset of standardized coin types is not yet available for most Greek coins (Wigg-Wolf and Duyrat, 2017). Therefore, we had to devise a way to identify unique types of coin designs to be able to quantify their informational values. In the next sections, we will discuss the issues we encountered in our attempt to standardize the descriptions of coin images available in online collections.

3.2.3. Measuring information in coin designs: the potentials and concerns of data standardization

There does not seem to be a definite answer for the long-standing questions concerning the meaning and function of coin designs (Elkins, 2009; de Callataÿ, 2018). Contemporary research tends to favour multidisciplinary approaches, assessing each case within its wider archaeological, historical and cultural context (Kemmers and Myrberg, 2011; Krmnicek and Elkins, 2014; Iossif and van de Put, 2016). Interpretations of coins and their images vary from focusing on their economic role as tokens of exchange carrying marks of authenticity, to seeing them as a widely circulating medium for political messages (de Callataÿ, 2016).

Looking for an alternative way to approach the meaning of coin designs, we focused on the information encoded in these graphic representations, and potentially communicated to the users. Information, in this sense, is understood as a statistical co-occurrence (a mapping) between an identifier and a referent – in our case, a type of coin design and a certain political entity (issuing authority) or a certain monetary value (denomination). This information-theoretic approach originated in research on communication technologies, and was developed by Claude Shannon and colleagues in the Bell Laboratories (Shannon and Weaver, 1949).

In information theory, entropy is a basic measure of uncertainty, quantifying the number of possible variants of a single variable (e.g., different types of coin designs). Entropy is maximal if all variants are equally probable, whereas a single possibility decreases the entropy to zero (i.e., the probability distribution is entirely predictable). When there are two corresponding variables, we can use conditional entropy to measure the uncertainty about the variants of one variable, while knowing the variants of the other, by comparing their respective frequency distributions. For instance, we can measure how well can we predict coin denominations in a given period by knowing the design types. Lower conditional entropy indicates a higher degree of predictability, and a better correspondence between the variants of the two variables in question. Low conditional entropy of denominations given designs thus signifies that coin designs contain some information about denominations. Conditional entropy has been used in the research on symbol-referent mapping in languages (Sproat, 2014; Winters et al., 2015; Winters and Morin, 2019), and we applied it to a system of graphic designs on ancient coins to compute their informational value as identifiers of issuing authorities and denominations.

We combined the data available from the *Sylloge Nummorum Graecorum* project of the British Academy (Carradice and Popescu, n.d.) and the *MANTIS* online database of the American Numismatic Society (2015), and prepared a corpus of unique coin types issued between c. 650 and c. 31 BCE, distributed approximately equally over 18 arbitrarily divided time intervals. For the purposes of the study, unique coin types were defined as coins issued in the same time interval by a certain authority, having a certain denomination, and marked with a unique design (Pavlek et al., 2019). Design types were constructed by combining obverse and reverse descriptions into alphabetically arranged strings of standardized motifs, following previously defined guidelines. As our study was solely concerned with graphic designs, inscriptions (letters, monograms, personal names, and place names) were not taken into account. We considered individual figures (persons, creatures, animals, plants, and objects), focusing on their general features and disregarding details such as posture, age, hairstyle, and clothing (including jewellery and armour). Similarly, we did not include motif repetitions and partial representations (head, forepart or hind part of an animal). Attributes (objects associated with a particular person), insignia (diadems, headbands, crowns, hats, staffs), and specific motif variants (incuse squares, helmets, and shield types) were coded separately. We standardized alternative spellings or terms for the same motif. In order to avoid introducing unnecessary changes to the data, we followed the original descriptions as close as possible. However, we identified two types of issues stemming from the fact that online collections are often compiled from multiple sources, by several different coders.

1. Identification of persons. For the most part, the persons depicted on coins are easily identifiable by their appearance and attributes as particular gods, goddesses, heroes, nymphs, or other mythological characters. However, due to the heterogeneity of sources, there are discrepancies regarding the identification of portrait heads, especially in the case of motifs known exclusively from poorly preserved or rare examples. The designs of two similar coin types (sharing date, authority, and denomination) could thus be interpreted differently, often as a result of the varying state of preservation or slight variations to be expected in coins struck by hand from individually cut dies. E.g., the female portrait head on Syracusan silver tetradrachms is variously described as "Arethusa", "nymph" or "(female) head" (compare the following coins from the *MANTIS* database, ANS 1997.9.20 and ANS 1984.46.12 dated 480-475 BCE; ANS 1997.9.39 and ANS 1997.9.42, dated 415-405 BCE).[2]

2. Addition, omission, and misidentification of motifs. In some cases, the descriptions either introduce motifs that are not present on the coin, omit motifs that are present, or confuse one motif for another. These issues can be a matter of subjective interpretation as much as a coding mistake.

The raw text format of these descriptions makes it hard to spot such inconsistencies, which may hinder standardization efforts. Including more detail increases the number of unique motifs, and by extension, unique design types. This, in consequence, influences the outcome of measures dependent on the frequency distribution of data types, such as the conditional entropy measure that we used in our study, by adding noise and obscuring or inflating the results of statistical analyses, especially when these analyses are performed on relatively small datasets. In the process of systematization and quantification of cultural data, it is necessary to apply a certain level of generalization and abstraction, which reduces the level of detail in the data – but the same is true of any classification system. Coding the data

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[2] Accessible online at: http://numismatics.org/collection/ followed by the catalogue number (e.g., http://numismatics.org/collection/1997.9.20).

consistently throughout the dataset, according to a pre-established standard, helps to avoid ambiguity and eliminates potential biases.

3.2.4. The level of detail and statistical measures: the implications of coding decisions

In order to illustrate the impact of coding decisions on the outcomes of statistical analyses, we used the dataset compiled for our previous study, and recoded obverse and reverse design descriptions adopting two extreme approaches to transform them into strings of individual motifs: a very fine-grained ("specific") and a very coarse-grained ("general") encoding. The basic set of considerations for identifying individual motifs remained unchanged: we disregarded variants of the same motif, including motif repetitions on a single coin and spelling variants. Table 3.1 summarizes the differences between the "general" and "specific" coding approaches.

GENERAL ENCODING	SPECIFIC ENCODING	EXAMPLE
rare motifs are replaced with more frequent equivalents (when available)	no generalization	boy → man apple → pomegranate
similar motifs are collapsed into a general category	no generalization	cockleshell, murex shell, scallop shell → shell
additional motifs (attributes, insignia) are not included	additional motifs are included → except for attributes appearing exclusively with a person *(attributes of a specific person appearing independent of this person are included)	diadem, sceptre, kausia (hat) *(pileus = cap of the Dioscuri, city walls crown = turreted crown of Tyche → included only when not appearing with Dioscuri/Tyche)
specific motif variants are not included	specific motif variants are included	incuse square types (different partitions), helmet types (Attic/Corinthian/Macedonian), shield types (Boeotian/Macedonian)
generic terms are used for persons instead of names → except for gods and goddesses (identifiable by attributes)	persons are named (when names are available)	king → Ptolemy I queen → Arsinoe II hero → Herakles heroine → Atalanta nymph → nymphArethusa river god →rivergodAcheloos

Table 3.1. Summary of coding guidelines for general and specific motif encoding.

We proceeded to explore the possible implications of these two coding variants on the conditional entropy measures, and on the diachronic trends of information about the authorities and denominations present in coin designs that we had identified in our original study (Pavlek et al., 2019). Each coding variant generated a different number of unique design types, resulting in two versions of the dataset characterized by a different number of unique coin types, sharing the same date, authority, denomination and design. We measured the conditional entropy of authorities and denominations given designs, respectively, over all coin types issued within each of the 18 arbitrarily divided time intervals. Even though the general trends look similar, the conditional entropy values display subtle differences between the original encoding and the two extreme variants (see Figure 3.1).

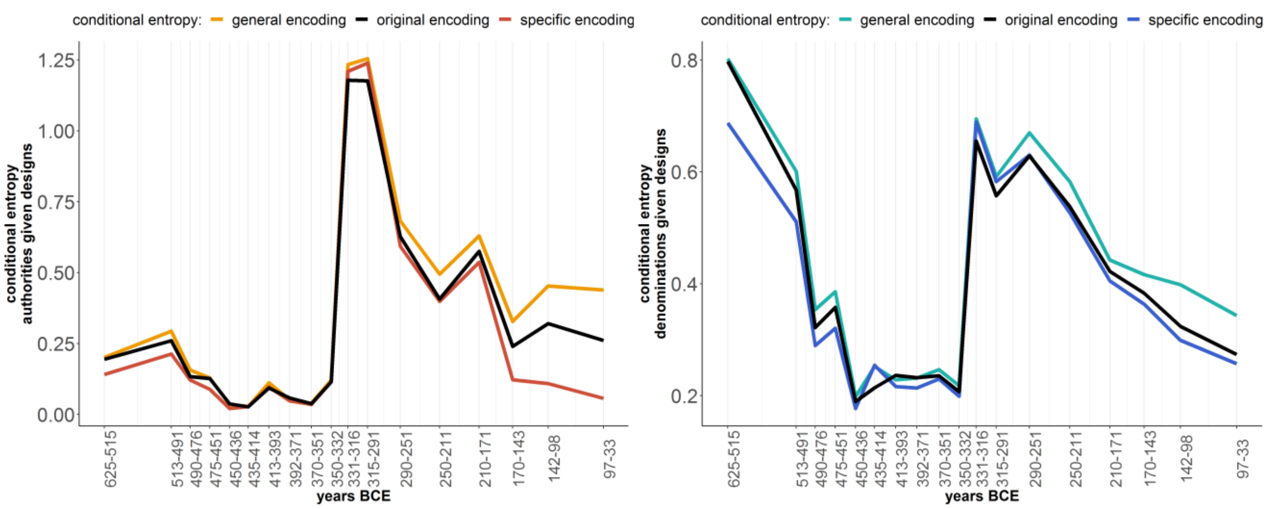

Figure 3.1: Diachronic change of conditional entropy of authorities given designs (left) and denominations given designs (right) through 18 time intervals, compared between the three encoding variants: original (black line), generalized, and specific (coloured lines). With time, coin designs become more informative about denominations (the conditional entropy of denominations given designs decreases), but not about authorities. In both cases, the peak in conditional entropy is influenced by the standardized coinage issued by Alexander the Great and his successors.

With these differences in mind, we can draw some insights on the influence of two coding alternatives on the frequency distributions of unique motifs, designs and coin types, and their subsequent effect on the outcome of information theoretic measures. This influence is especially noticeable when considering the difference between the general and specific coding of portraits of historical and mythological persons. In line with the guidelines presented in Table 3.1, persons are coded using generic terms (“king”, “queen”, “nymph” etc.) in the general coding variant. In the specific coding, the persons that the experts identified based on the coin legends (inscriptions) or inferred from the context (the time and place of the coin's issue), were labelled by name. When the source databases omitted the person's name, as in the example of the Syracusan nymph Arethusa cited above, we assigned the names based on the analogous coin types, verifying the suspicious cases in the referent literature (Head, 1911; Kraay, 1976).

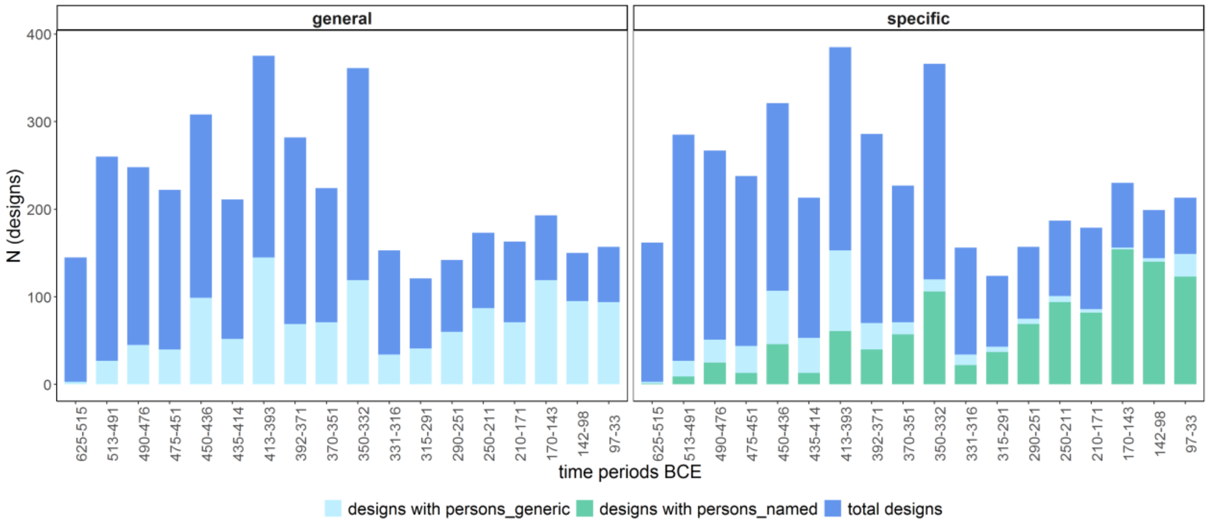

Figure 3.2: Frequency distribution of unique design types (blue) in the "general" and "specific" datasets. The designs featuring generic persons ("king", "nymph" etc.) are marked in light blue. The designs featuring named persons (e.g., "Ptolemy I", "nymphArethusa") are marked in green.

Figure 3.2 presents the number of unique design types over 18 time intervals, highlighting the proportion of designs featuring persons. In the "specific" dataset, most persons depicted on coins are identifiable by name, especially in the later periods. Treating them as individual motif types, separate from the generic, unnamed persons, adds to the diversity of motifs composing the designs. This contributes to the increase of the basic entropy of designs (see Figure 3.3), making them less predictable. Additional design types in the specific coding affect the mapping between designs and authorities or denominations (frequencies of unique denominations and authorities being constant for each of the coding alternatives), inflating the estimates on the amount of information in coin designs. This is why the "specific" designs are overall more informative (indicated by lower conditional entropy values in the final periods) than the "general" ones, especially about the issuing authorities (see Figure 3.1).

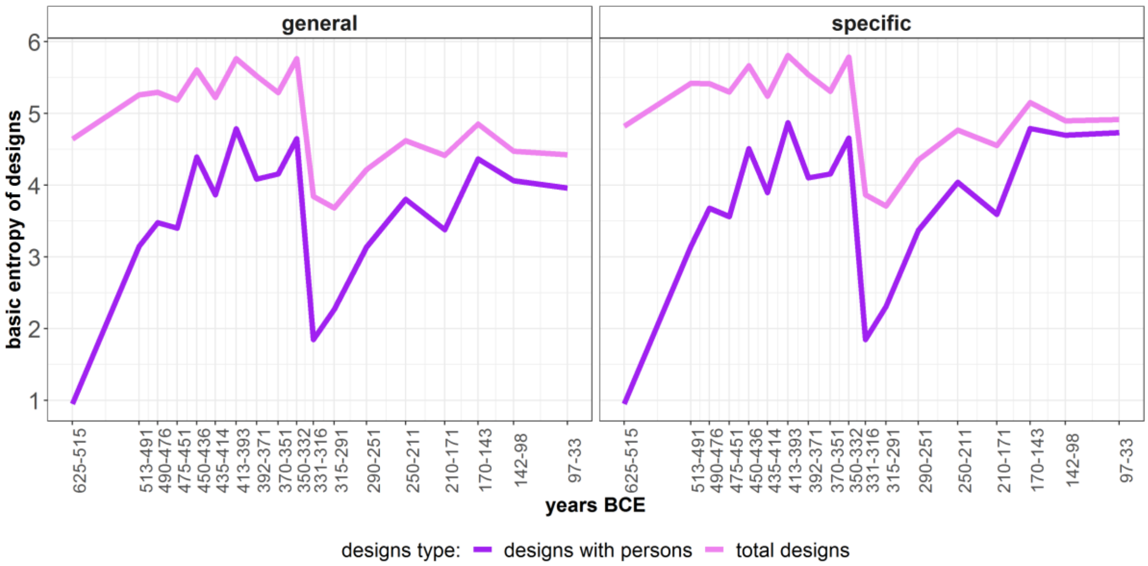

Figure 3.3: Diachronic change of basic entropy of designs, measured for "general" and "specific" versions of the dataset through 18 time intervals, separately for designs featuring persons (purple line), and all other designs in a period (pink line).

In the Hellenistic period, following the death of Alexander the Great, portraits of rulers appeared on coinage, replacing images of gods and heroes (Carradice, 1978). The portraits of mythological persons, despite their generic character, are identifiable by their attributes, e.g., a lion-skin for Herakles or a helmet for Athena. Hellenistic royal portraits, unlike the generic depictions of the Persian Great King, do display a considerable level of individuality (Carradice and Price, 1988, p. 123 ff.). However, some portraits also tend to be stylistically similar and emphasize the resemblance between the members of the same dynasty, meant to signal continuity and legitimacy of the rulers as heirs of Alexander (Thonemann, 2016: 145 ff.). The attribution of a portrait to a particular historical ruler is thus largely reliant on context: ruler portraits usually appear on their respective coins, often accompanied by inscriptions denoting them as the issuing authority. The existence of inscriptions on coins would assume a certain degree of literacy in their users, and add to the information encoded in the coin. However, before the middle of the 5th century BCE the inscriptions were rare and mostly limited to place names ("ethnics"), followed by the names of rulers and magistrates in the later periods (Carradice and Price, 1988, pp. 57–60; Kraay, 1976, pp. 2–7). By contrast, gods and mythological beings were rarely explicitly named. Nevertheless, as most coins were produced and used locally, it is likely that the contemporary users could recognize the persons depicted on coins, even if recognizable attributes or labels were missing (Weir, 2010).

The ambiguity of designs featuring persons, however, often presents a problem for modern numismatists striving to describe and classify them. It is therefore important to consider the way we code the coin designs, choosing the appropriate level of granularity depending on the hypothesis we are planning to test. In the case of our recent study, since our hypothesis was concerned with the information encoded in the coin's graphic designs, a generalized coding approach seems to be more appropriate to capture the information directly present in the images, and to avoid introducing artificial complexity derived from the inscriptions and general historical context.

3.2.5. Conclusion

The last decade has witnessed a growing number of digital resources, advancements in computer-assisted approaches, and the development of standards for annotating cultural data. This opened new possibilities for management and presentation of cultural heritage. Standardized databases present a way to organize the data, making it more reliable and available for research, suitable for testing different questions using a variety of approaches. However, many challenges remain, especially concerning the digitization of collections of material culture, where finding a generally applicable standard to describe graphic representations seems to be particularly difficult.

In this article, we focused on coins, objects marked with graphic designs, produced in large quantities and disseminated mostly by political authorities, serving primarily as media of exchange. Their official character, together with a substantial number of examples preserved since antiquity, make them particularly suitable for standardization. In the field of ancient history, numismatics has been one of the early adopters of linked open data principles in developing standards for organizing digital collections and making them available to wider audiences. However, the focus of these standards is still on the technical properties of the coins, their provenance and value. Although reliable online catalogues listing the types of coin images are available for some areas of numismatics, no general standard exists for representing coin iconography.

This lack of standardized descriptions hinders the possibilities for studying large diachronic patterns of structure, evolution, and transmission of images using quantitative methods. The use of statistical measures and models requires the data to be in an unambiguous, standardized format. In order to be able to observe the "big picture" quantitatively, it is necessary to adopt some degree of generalization, albeit at the expense of detail. On the example of our study on the informational value of images on ancient Greek coins, we illustrated the importance of standardized data for quantitative studies, and pointed out some issues worth considering when developing standards for encoding images. We showed the advantages of a generalized coding approach, focused on basic concepts rather than their specific manifestations and variations, over a specific coding, capturing a greater level of detail, but introducing noise in statistical measures.

Current attempts at creating standards for annotating coin images, based on semantic ontologies, strive to offer a certain amount of flexibility, while not risking losing any data. This approach is certainly appropriate for general databases intended for research purposes, provided the detailed concepts are well accepted. Otherwise, an overly specific standard might be less interoperable. Ideally, standardized iconographic descriptions should be based on a minimally extensive list of well-defined concepts, supplemented with references to the relevant literature. The ongoing efforts in digitization of reference catalogues, development of computer-assisted methods for image identification, as well as further application of linked data principles allowing the integration of existing data standards and the development of new ones will undoubtedly expand the possibilities of future research on coin images and visual culture in general.

4. Reverse engineering cash: cognitive background of coin properties

4.1. Author contributions

The study presented in the following chapter has been published in the journal *Cognition* in May 2020 (https://doi.org/10.1016/j.cognition.2020.104182). The study was conducted by Barbara Pavlek under the supervision of Olivier Morin and in collaboration with James Winters (The Mint, MPI-SHH). The study was conceptualized by Olivier Morin, and all three authors were involved in study design. The data were collected and curated by Barbara Pavlek, who also conducted the analyses with help from the co-authors. All three authors have contributed to the writing of the manuscript.

The authors thank Julia Bespamyatnykh, Moritz Dörfler, and Noro Schlorke for their help in collecting and coding the data, as well as Thomas Müller and Piers Kelly for their valuable input.

The main hypotheses and predictions tested here were preregistered on the Open Science Framework, along with the methods, statistical tests, and data inclusion criteria (see Appendix 2). The preregistration can be accessed at https://osf.io/ekcdb/ (see Appendix 2, section 1). Post-hoc analyses are explicitly signalled as such. A second preregistration, addressing reviewers' comments, can be accessed at https://osf.io/tkj8y (see Appendix 2, section 3).

The complete dataset and the code associated with this paper are accessible at this address: http://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fcd7d2.

4.2. Pavlek, Winters, Morin (2020). Reverse engineering cash: Coin designs mark out high value differentials and coin sizes track values logarithmically

4.2.1. Introduction

When evaluating sums of money, we are subject to biases such as the money illusion (where one hundred cents appear greater than one dollar; Shafir, Diamond, and Tversky 1997). Perceived physical magnitudes (e.g., sizes) interfere with our perception of monetary quantities (Goldman et al., 2012). Crumpled bills appear less valuable than bills in mint condition (Di Muro and Noseworthy 2013). Bills are seen as more valuable than coins, keeping values equal (Dolansky, 2014; Tessari et al., 2011). We are less likely to part with a 50 euro bill than to let go of five 10 euro bills (Mishra et al., 2006; Raghubir and Srivastava, 2009).

These studies, together with the rich literature on the perception of coins and their value (following Bruner and Goodman 1947), show how the appearance of cash money can influence economic behaviours. Yet, little research has investigated whether coin properties reflect these biases. The relationship between cultural artefacts and cognitive biases can be studied experimentally, but it can also be observed by analysing cultural data directly (Kelly and Keil, 1985; Sperber and Hirschfeld, 2004). Testing hypotheses on real-world corpora is a fruitful method in linguistics (Kemp and Regier, 2012; Piantadosi et al., 2011) and elsewhere. Studying the shape of letters in the world's writing systems, for instance, reveals formal constraints derivable from the structure of visual cognition (Changizi and Shimojo, 2005; Morin, 2018). The invention of written letters took into account readers' visual biases; likewise, coins should be sensitive to the way coin users represent physical and monetary magnitudes. Testing this point is of practical interest, to promote ergonomic currencies and avoid costly design errors. On a theoretical level, it links the study of numerical cognition with research on everyday economic behaviour.

This study, covering the most recent coin series in circulation for the world's currencies, shows how the appearance of coins reflects their value. Modern coins indicate their nominal value in writing, but also through their size, their colour, and the images minted on them. We focused on the differences between "adjacent pairs" of coins, i.e., any two coins of neighbouring values belonging to the same currency (e.g., two cents-five cents, one euro-two euros). We considered differences between these coins' colours, sizes, and "designs" (the images on both sides of a coin, excluding inscriptions and value marks). We hypothesised that two coins are more likely to be distinct to the extent that they differ in value.

The task of encoding monetary values with images (i.e., designs) raises a problem that verbal labelling also faces: a trade-off between simplicity and informativeness (Regier et al., 2015). Minting all denominations with one identical image would result in designs that carry no information about denominations (informativeness deficit). Conversely, minting each denomination with a different design may put excessive pressure on the users' memory and attention (simplicity deficit). Even frequent words are exposed to a simplification pressure keeping word inventories low. Such trade-offs are typically solved by taking into account the users' communicative needs (Gibson et al., 2017; Kemp and Regier, 2012). For currencies, similar pressures likely obtain, given the difficulties experienced by infrequent (Vranka et al., 2019) and even frequent coin users (Gallup & Eurobarometer, 2006; Kantar Public & Eurobarometer, 2018) in telling coins apart.

On this basis, we hypothesised that coin designs should be distributed over the different denominations of a given currency in a cost-sensitive fashion, taking into account the value differentials between denominations, which are identical to the cost of mistaking one denomination for another. Considering, within each currency, all pairs of coins of adjacent value, the chances that the designs minted on both coins differ should increase along with the pair's value differential (e.g., one cent for the one cent–two cents pair, three for the two cents–five cents pair, etc.). (Prediction 1.1.) We also expected the differences in colour between the coins in such a pair to reflect the value differentials in a similar way as proposed for coin designs. (Prediction 1.2.) (The "colour" of a coin's metal alloy is reminiscent of precious metals—copper, silver, gold—historically used in coin production, and now associated with coin values.)

The relation between coin sizes and coin values raises a different issue. Monetary value and diameter size are continuous quantities: they can be mapped onto each other by making coin sizes co-vary with their face value (e.g., one cent for a one-cent coin). Accordingly, we expected that size differentials in pairs of coins of adjacent value ("adjacent pairs") would correlate with value differentials (Prediction 2).

What exact shape should this value-size correlation assume? Two independent research traditions, psychophysics and the theory of marginal utility, can be read as implying that monetary values are represented on a logarithmic scale. Marginal utility theory and its precursors (starting with Bernoulli, 1738/1954) assume a logarithmic mapping between a sum of money and the utility derived therefrom. Prospect theory incorporates this view in the way that it models loss aversion (Kahneman and Tversky, 2012). Psychophysics, building upon the work of Weber and Fechner, has shown that the representation of prices tends to follow Weber's law (Cheng and Monroe, 2013; Dehaene and Marques, 2002). As a consequence, the same price differential is less likely to be noticed in a high price range, compared to a low-price range. As far as we know, this claim concerning the perception of prices has not been generalised to other types of monetary quantities, such as the value of coins. We predicted that log-transformed values would predict size differentials better than non-transformed values, since, in our view, coin designs should track monetary quantities as represented by the numerosity system (Feigenson et al., 2004). By the same logic, log-transformed values should also provide a better predictor of whether two coins share the same design or colour (Prediction 3.). We aimed to test these predictions on all coins in circulation today.

4.2.2. Methods and Results

Our predictions, methods, and models were preregistered on the Open Science Framework[3]. All preregistered analyses and their associated results are reported there[4]. The analyses described here occasionally include data inclusion criteria and model specifications that differ from the preregistered ones. These changes do not affect the results of the preregistered analysis (AIC differentials, direction and significance of fixed effects estimates, etc.). Since there is, to our knowledge, no pre-existing literature on the particular effects that we predicted, no power analysis was carried out, but we made sure that our sample was exhaustive in the sense that it included all currencies in use today, as listed by the International Organisation for Standardisation (ISO).

We assembled a corpus of 182 currencies, comprising 1132 coins (950 adjacent pairs). Information concerning designs, colours, and diameter sizes was gathered from the respective central banks' websites and the Standard Catalogue of World Coins (Cuhaj 2015),

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[3] http://osf.io/ekcdb/

[4] https://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fcd7d2

supplemented by two online sources (Wikipedia and Numista catalogue). We took into account only the most recent coin denominations currently in circulation, disregarding infrequent older variants as well as commemorative coins. For each pair, we asked two independent coders to determine, based on written descriptions, whether the two coins had the same design (0) or not (1)[5]. They agreed upon 943 pairs and disagreed upon seven (Cohen's kappa = .98), which we discarded from all analyses bearing upon design differences. All nominal values were standardised as multiples of the value of the smallest coined denomination in each currency, or "Smallest Coins". The Smallest Coin for euros is one cent, so two euros are worth two hundred Smallest Coins, whilst the Smallest Coin for the Vietnamese dong is two hundred dongs, thus five thousand dongs = twenty-five Smallest Coins. Value differentials between pairs of coins of adjacent value were similarly standardised (e.g., the differential between one euro cent and two euro cents is one Smallest Coin; that between one euro and two euros is one hundred Smallest Coins).[6]

To test prediction 1.1, we focused on the currencies that produced at least one adjacent pair of coins with identical designs, and one pair with different designs. We excluded the currencies that systematically bear a different design on every denomination (n = 99), along with those that carry the same design on all denominations (n = 19). Excluding these currencies does not change the results given below. We built three mixed effects logistic models to predict, for all adjacent pairs of coins (n = 386) in each currency (n = 64), whether the two coins' designs were the same (0) or different (1). For instance, the two-cents and five-cents German euro coins share the same design: an oak leaf on the German side, a globe and twelve stars on the common side. The five-cents coin and the ten-cents coin bear distinct designs (the ten-cents coin features the Brandenburg Gate and a map of Europe). The first, "null" model included a random intercept for each pair's currency. A second model, which included the value differential between coins (in Smallest Coins) as a fixed effect, proved more informative than the null model ($\Delta_{AIC} = 7.60$). A third model was built, identical to the previous one except for the fact that value differentials were log-transformed. It proved more

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[5] Our test of prediction 1.1. was repeated using a different measure of design similarity in adjacent pairs. Two independent coders judged whether the two designs were the same (0) or different (1) by comparing pictures of coins, not written descriptions (Cohen's kappa = .90). The results replicate the pattern of significant results reported in this paper (see sup. mat, sections 4.1 and 4.2.1).

[6] The analyses presented below were also all replicated using a different measure of coin value (US dollar equivalents: sup. mat. section 3.2), with no change to the pattern of significant results reported here (see sup. mat. section 4.2).

informative than both previous models (Δ_{AIC} = 17.09 compared to the null) and included a positive estimate for value differentials ($\beta = 0.31$, SE = 0.07, z = 4.16, $p < 0.0001$). Designs are more likely to differ between adjacent coins to the extent that these two coins are far apart in value (like one euro - two euros vs. one cent - two cents), verifying prediction 1.1. (Figure 4.1). Following prediction 3, log-transformed value differentials are a better predictor of this phenomenon than raw value differentials.

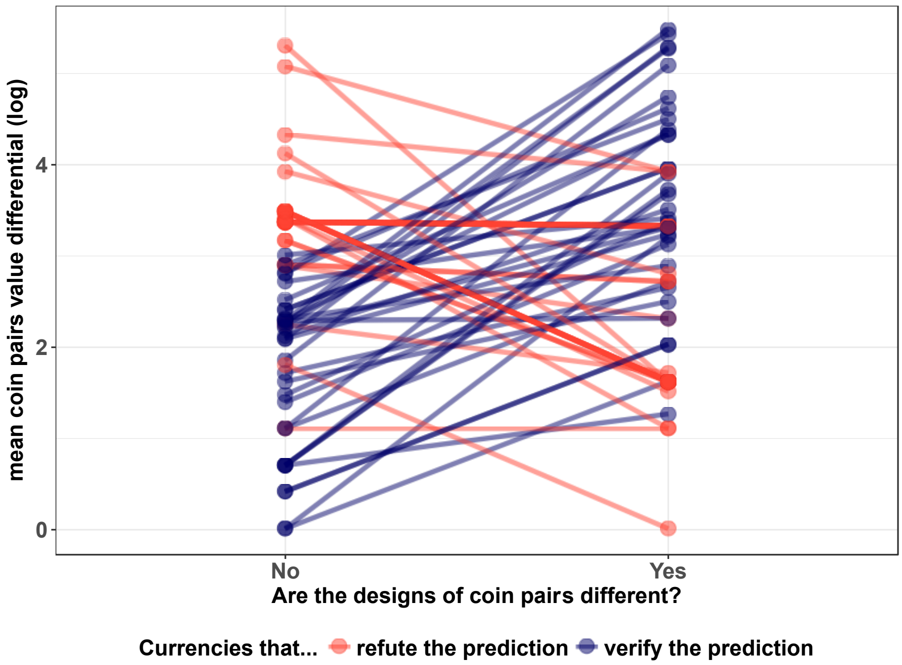

Figure 4.1. In pairs of coins with higher value differentials, coins are marked with distinct designs. Each line stands for one currency (total n = 64), and shows the average value differential between adjacent pairs of coins (e.g., one euro-two euros), depending on whether or not the two coins share the same design (left) or have different designs (right). The majority of currencies verify our prediction (in blue): pairs bearing distinct designs tend to show higher value differentials. Value differentials are given in Smallest Coins, i.e., as multiples of the value of the smallest coined denomination within each currency.

The same effect applied to coin colours: the more two adjacent coins differed in (log-transformed) value, the more likely they were to differ in colours (prediction 1.2.). Log-transformed values predicted this better than raw values (prediction 3). This prediction was tested on 950 adjacent pairs of coins. The first, "null" model included a random intercept for each pair's currency. A second model, which included the value differential between coins (in Smallest Coins) as a fixed effect, did not prove more informative (Δ_{AIC} = 1.13 in favour of the null model). However, a third model, identical to the previous one except for the fact that value differentials were log-transformed, proved more informative than the null model

(Δ_{AIC} = 39.30) and included a positive estimate for value differentials ($\beta = 0.28$, SE = 0.05, $z = 5.98$, $p < 0.0001$).

To test prediction 2, we treated all twenty-three national series of the euro as one single currency, and similarly "collapsed" the two variants of the French Pacific franc. These families of currencies showed no internal variation in coin sizes, while exhibiting clear internal variation for designs. Collapsing them does not change the results given below. We built two linear mixed effects models to predict the size differential between coins (diameter size differential, in millimetres) for all adjacent pairs of coins (n = 790) in each currency (n = 159). The first, "null" model included a fixed effect controlling for whether or not the two coins were of a different colour, a random intercept for each pair's currency, and a random slope reflecting the effect of the colour difference for each currency. This "colour difference" predictor always made the model more informative and had a strongly negative effect. In other words, in pairs straddling a colour divide (e.g., "copper" five euro cents – "golden" ten euro cents), the size differential between two denominations is on average less important, compared to pairs where both coins have the same colour. The null model was compared with a second model, which included an additional fixed effect for the value differential between the coins in a pair (in Smallest Coins, log-transformed). That second model did not prove more informative (Δ_{AIC} = 1.48, in favour of the null model). We found a clearly positive intercept ($\beta = 2.35$, SE = 0.18, $t = 13.12$, $p < 0.0001$), indicating that the higher-value coin of the pair is on average larger than the lower-value coin. These results remained unchanged if we excluded four outlier pairs presenting excessive size or value differentials, or if we considered only the pairs of coins that do not differ in colour. Prediction 2 is thus refuted: size differentials do not increase with value differentials.

Just because value differentials fail to predict size differentials does not mean that absolute coin sizes do not reflect absolute coin values. The preceding result strongly suggests that they do, since higher-value coins in a pair are larger. In an unregistered follow up, we tested an additional prediction: absolute coin sizes reflect absolute coin values. In keeping with the logic of prediction 3, coin sizes should track log-transformed coin values better than raw coin values. We thus considered the absolute size and value of individual coins (as opposed to the size differentials between the coins in an adjacent pair). We again collapsed the Eurozone and Pacific franc currencies to one data point each (resulting n: 949 individual coins from 159 currencies) and compared three linear mixed effects models. The first, "null" model predicted each individual coin's size with two random intercepts, one for currency, and one for colour. This model was outperformed by a model including each coin's value (in Smallest Coins) as a fixed effect (Δ_{AIC} = 14.54). That model was, in turn, outperformed by a third model using log-transformed values (Δ_{AIC} = 553.87). Like the previous one, this model included a strong and significant estimate for the effect of coin value (β = 1.58, SE = 0.04, t = 34.61, $p < 0.0001$). Removing 16 outlier coins with abnormally high values did not change this pattern of results: coin sizes reflect coin values on a logarithmic scale (Figure 4.2).

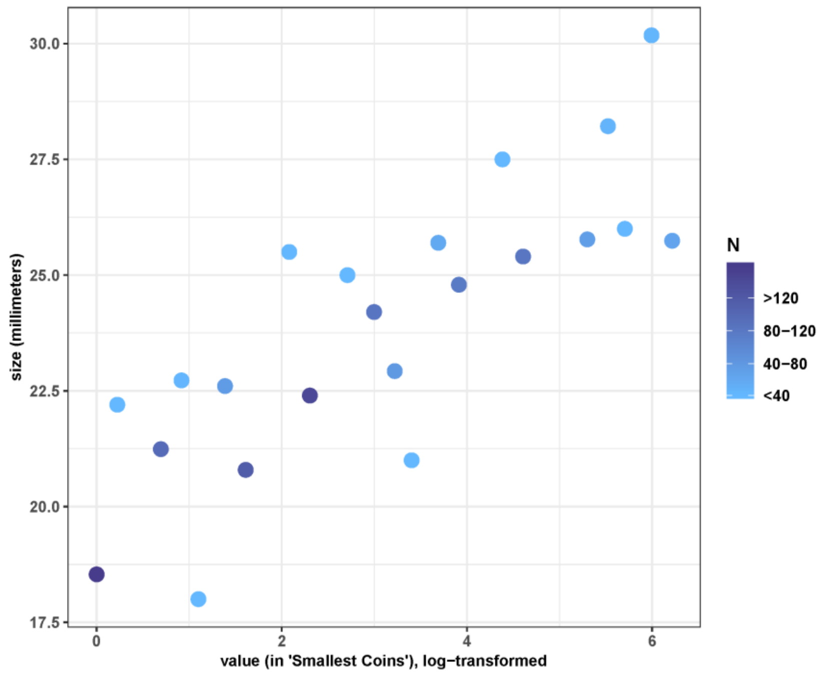

Figure 4.2. The size of coins reflects their value on a logarithmic scale. Each data point is one set of coins sharing the same value (with number of coins indicated by dot colour). (Total n: 933 coins from 159 currencies, excluding 16 outlier coins.)

4.2.3. Discussion

Our tests of predictions 1.1. and 1.2. confirm that coin designs and colours are distributed in an economically efficient way, minimising the cumulative cost of confusing coins. Prediction 2 was not supported: high value coins tend to be bigger than low-value coins, but not necessarily in proportion to the value differential between them. Our third prediction, that log-transformed differences in value matter more for coin structure than the raw differentials, was verified for coin designs but could not be tested for size differentials. We found support for a related but *post hoc* prediction: individual coin sizes track coin values on a logarithmic scale.

Psychology does not generally praise the ergonomics of coin designs (Horner and Comstock, 2005), mostly because of Nickerson and Adams' widely cited study (1979), whose subjects were surprisingly mediocre at recollecting in detail the features of the 1972 one-cent ("penny") USD coin. In the same study, however, participants remembered with near-perfect accuracy the features that made the penny design distinctive from other USD coin designs (i.e., Lincoln and his memorial). The features they failed to remember were the ones that the penny shares with other coins (e.g., the word "Liberty"), or those that could be changed without making pennies any less distinctive (e.g., which side Lincoln faced). Distinctive design features play a crucial role in identifying coins, superior to other features such as size, thickness, or indentation (Horner and Comstock, 2005). The sparse encoding of coin designs that Nickerson and Adams evidenced should thus be understood from an efficiency point of view: people only burden their memories with useful design features. As our data suggest, coins assist the users in solving this trade-off, only requiring them to memorise relevant designs.

The fact that coin designs are more informative for high value differentials confirms that human communication creates categories that satisfy an informativeness-simplicity trade-off while respecting functional constraints. 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 findings are also coherent with those of a previous study (Pavlek et al., 2019) on Ancient Greek coins, showing that the designs of high-value coins carry more information concerning their denomination, compared to the designs of low-value coins. Both ancient and modern coinage displays a non-linear denomination structure, with larger value differentials in the higher-denominations range. Differences in value between adjacent coins or bills increase in a roughly exponential manner (Bouhdaoui et al., 2011; Wynne, 1997). Larger value differentials between high value coins are worth signalling with distinctive designs, since these coins are more costly to confuse.

Our results also suggest, in three different ways, that log-transformed coin values predict the structure of coin properties (size, colour and design distinctiveness) better than raw values, in line with work showing that people represent prices on a logarithmic number line (Cheng and Monroe 2013; Dehaene and Marques 2002; Marques and Dehaene 2004, but see Fitousi 2010). Such logarithmic representation is a signature of the "numerosity system", a specialised mental faculty dealing with estimates of approximate magnitudes (Feigenson et al., 2004). Such a system appears well equipped to process the economic utility derived from money (as distinct from the face value of coins), since it is assumed to follow a logarithmic relationship. Should this system be recruited in processing coin values, this would make sense of interferences between perceived physical magnitudes and perceived monetary values: prices that seem more expensive when printed in a bigger font (Coulter and Coulter, 2005), coins whose estimated size changes depending on their value (Furnham and Spencer-Bowdage, 2003). Overall, the present findings show coin designers to be intuitive psychologists, making imperfect but clear use of sound cognitive and ergonomic principles (Norman, 2013).

5. General discussion and conclusions

Coins are physical representations of monetary value. In order to be used as a medium of exchange, a coin has to contain enough information for the users to be able to recognize it as a valid means of payment of a certain value. In the case of Western coined money, stemming from the Greco-Lydian tradition, this informative role is often fulfilled by graphic designs, marks of an issuing authority whose political and economic power guaranteed the coin's value. Through the course of their evolution, coins played various roles in the changing political and economic circumstances, which in turned shaped their material and symbolic features. The general aim of this thesis was to explore the evolution of coins as an informational system. Studies conducted in the course of this doctoral project were presented in three chapters, which are published or submitted as articles in peer-reviewed journals, accompanied by openly available code and datasets used in the analyses, adhering to the principles of open science.

The first study, presented in Chapter 2, focused on ancient coins from their invention in the later 7th century BCE in the Lydian kingdom and Greek polities on the Ionian coast of Asia Minor, until the end of the 1st century BCE, when the Romans established their rule in the eastern Mediterranean. In these six centuries, coins spread among Hellenic polities and their neighbouring states across the Mediterranean through trade and migrations, and through the conquests of Alexander the Great, which brought coins all the way to India. Because they were made of precious metals, the value of ancient coins was based primarily in their metal composition and weight. However, what set coins apart from other commodities used in exchange was their official status, established by the mark of authority. Most theories suggest that the primary function of images put on coins was to identify the issuing authority. Still, by marking coins with their official "seal", authorities were able to regulate their exchange value and establish control over monetary production, which enabled them to gain a profit. In this sense, even though coin designs primarily represented the power of authorities, they also contained some information about the coins' value.

Applying measures based on information theory to quantify the information content of coin designs made it possible to analyze diachronic trends for different types of information. The results show that, with time, coin designs became increasingly informative about the coins' monetary value. This type of evolutionary dynamics, which sees the connection between the symbols and their referents solidify over time, can be found in other communication systems, both linguistic and non-linguistic (e.g., graphic codes in artificial language experiments, or evolving writing systems). However, the pairing between the two features was not found to be more consistent, which would suggest that, although designs gradually became geared towards representing denominations, the system did not become more structured. In contrast, early designs were already successful at indicating issuing authorities, but the political circumstances made this connection weaker. Growing networks between polities enabled the diffusion of images, techniques, and artists, which reduced the distinctiveness of coin designs. This process was particularly influenced by political integration, especially in the time of Alexander's empire, where the existence of a single dominating authority made signalling the coins' provenance less relevant.

The presence of state-relevant, political information in coin designs is not surprising – most interpretations of coin designs, based on ancient sources and on a long tradition of numismatic research, emphasize the political significance of these images. On the other hand, the presence of value-relevant, economic information in the designs of early coins, despite them lacking explicit marks of value, supports the theories arguing that a certain level of fiduciarity was present in ancient coins made of precious metals. Marking coins with graphic designs allowed authorities to regulate the exchange value of coined money, convince users of its validity, and enable its use in market economies. Images played an instrumental role in the evolution of monetary policies, in the creation of monopolistic closed economies or monetary unions, and in the introduction of bronze coinage, which provided the basis of large-scale monetary systems like the ones developed by Rome.

These results match well with previous research on the nature and role of Greek coins and their designs, while also providing a new angle to some known issues. The research on coin designs has long focused on understanding the meaning of specific designs, and how it changed through time, and on explaining the reasons behind the diffusion of images among different polities. More recently, the availability of large digital collections of data on ancient coins has enabled researchers to compare individual coins and their images taking in account their frequencies and distributions. The present work adds to this research direction, by successfully applying measures based on information theory to examine whether the structure of coin designs corresponds to the issuing authorities and denominations issued by these authorities in a certain period. These measures have a potential to go beyond counting distinct variants and offer a deeper understanding of the underlying principles and diachronic political and economic trends behind the observed patterns of graphic designs, contributing to research highlighting the role of state authorities on one hand, trade and markets on the other, in shaping the early history of coinage and monetary economy, reminiscent of Keith Hart's metaphor of a "two-sided coin". This approach also shows the enormous potential of digital databases for the studies of large diachronic trends, and could potentially be expanded to test relevant questions on large collections of other image-bearing material, such as seals or pottery.

In the last couple of decades, discussions on the application of computational methods and statistical analyses in social sciences created a movement towards more open, methodologically sound and collaborative research paradigms. Openly sharing data and code used for analyses, as well as clearly stating hypotheses and predictions, improves research reproducibility by enabling independent validation of results. Projects creating and managing large databases of cultural data also embraced these principles, and focused on developing reliable and widely accepted standardized data formats, concepts, and ontologies, as well as strategies to overcome data uncertainty by combining the input from multiple sources or expert coders and factoring in the level of agreement between them.

However, despite their size and availability, most databases of cultural data are designed primarily as collection catalogues, and some do not conform to the standards necessary for quantitative research. Without agreeing upon standardized ways to describe and quantify cultural data, large-scale studies of human history risk arriving at erroneous conclusions, despite the use of powerful, complex models, and "bigger" datasets. Although there has been a lot of progress in the development of general and domain-specific standards for describing and classifying cultural data, the lack of standardized approaches to images and image-bearing objects makes it difficult to construct reliable datasets. Moreover, the decisions we build in the datasets inevitably affect any statistical analyses we want to run on these data. This problem is not limited to iconographic material or coins, but it is widely present in research on cultural phenomena, especially in historical periods.

These methodological issues were addressed in Chapter 3, highlighting the need for standardized descriptions of coin designs as a part of digitized catalogues, which would enable further research on coin iconography using quantitative methods. Standardization entails careful consideration of the features present in the data, but also of the influence of the researchers that collected it. Computational methods offer a more objective approach to analysis and interpretation, but their outcomes largely depend on the properties of the underlying dataset. Statistical analyses and models operate with a set of assumptions, and require the data to be well defined, often expressed in numerical terms and formatted in a specific way. Meeting these requirements poses a problem for the large-scale research on cultural phenomena, most of which are not readily quantifiable.

Defining the main unit of analysis still presents a methodological and theoretical issue in the field of cultural evolution. The focus on material culture in archaeology has made this issue slightly less complex than e.g., in linguistics, because physical objects can be counted and measured, and their composition and age can be assessed with numerous archaeometric methods, from radiocarbon dating to isotope analysis. On the other hand, symbolic and "stylistic" elements of material culture are more problematic to analyze and interpret. Individual, small-scale approaches to these cultural features enhance our understanding of their role in a specific historical context, but are often limited in inferring causation. While it is necessary to be cautious in our interpretation of the past, and aware of the limitations of inferences based on the incomplete data recovered from the remains of material culture, these limitations should not discourage further research. Although it cannot provide a definite answer to every question, statistics is a useful tool for discriminating between more and less probable explanations and checking the robustness of our theoretical assumptions. Despite being challenging to implement, computational modelling can help connect the findings of detailed analyses in order to reconstruct and understand the long-term processes unfolding on a much bigger scale.

Apart from computational data analyses, research on human history is profiting from an increasing interest in the mutual influence of cognition and culture, using experimental and comparative methods to investigate particular or universal cognitive mechanisms that affect our perception and interaction with the physical world and other individuals. In Chapter 4, this approach was taken to investigate whether the properties of contemporary coined currency reflect some underlying cognitive biases in their makers and in their users. Many such biases were uncovered through a substantial amount of research in psychology focused on the perception of monetary value and (to a lesser extent) on the physical properties of coins and banknotes. Despite the value of modern coins being clearly established by national banks, and in most cases prominently marked on the coin's surface, users still largely rely on graphic designs, size, weight, shape and colour to recognize coin denominations, which are misunderstood more often than one would expect from such a seemingly simple system.

This study explored how monetary value is encoded in coin properties, and communicated to users. The results indicate that coins of contemporary currencies are specifically designed to represent monetary value. The logarithmic shape of the relationship between properties and values of coins seems to indicate that coins function as a system of signs, interacting with human cognitive faculties in a similar way as other systems describing magnitudes, such as numbers or measurements. These results also suggest that coins form an informational system that, similar to linguistic systems, is designed to give users enough information to be able to recognize coin denominations, without becoming overly complex. The abstract concept of monetary value is materialized in coin denominations, fractional units of a currency. The structure of denominations, their number and specific values, is devised to be efficient, both in terms of production costs, and in order to serve as a flexible and simple system of tokens of exchange, allowing all transactions to be carried out with a minimal number of tokens. This principle is also reflected in the way coins are designed, striving to satisfy the requirements of producers and users by being affordable, usable, and informative.

An interesting finding of the study on ancient coins presented in Chapter 2 was that the coins of higher value were on average marked with more informative designs than coins of lower value. A potential explanation for this pattern could lie in the denominational structure of ancient currencies, which was similar to the modern one: greater differences in value between larger denominations made them more costly to confuse, and could lead to the need to indicate their values more saliently. Modern minters take notice of experiments showing people's attitudes towards coined money, but design decisions are often concerned more with politics and tradition than psychology and ergonomics. Monetary authorities are reluctant to change the properties of their coins, because users tend to form specific expectations about how "valid money" should look like, and are unwilling to accept any significant change. Economic and political laws shaped coin properties and their values thorough history. This has left a mark on people's perception of coins and money, and affects their attitudes and economic behaviour. While many aspects of the nature, function and meaning of ancient coins might be lost to us, many features of coinage stayed stable through their long evolution, leaving evidence which could be uncovered through comparative and experimental approaches. However, this evidence has to be carefully examined in the light of information provided from other historical sources, to avoid overly anachronistic interpretations.

The work presented in this thesis attempted to provide novel perspectives to some long-standing questions concerning the role of coins as an economic and political medium of exchange and communication, by applying interdisciplinary methods and theory from evolutionary anthropology, information theory and cognitive science. Hypotheses about diachronic patterns of cultural change can be tested quantitatively using large online databases developed over the last couple of decades. Such computational approaches allow us to examine individual objects in relation to others that are created and used in the same historical context, and offer a way to uncover the causal mechanisms shaping their evolutionary history.

The focus of this project was on the primary role of coins as monetary objects. Interpreting the specific functions and meanings that coins and their designs assumed in different contexts, from the political to the religious, from the private to the public sphere, requires methodologies that differ from the interdisciplinary approach adopted here, which is meant to be an addition to, rather than a replacement of, more traditional research paradigms. Coins are a unique historical source, combining different features (material, image and text) to transmit various types of information over long temporal and spatial distances. These characteristics, along with their number and availability, make them an ideal candidate for studying large-scale diachronic processes of human cultural evolution. Additionally, acknowledging and investigating the influence of cognitive mechanisms and biases on all aspects of human culture opens a way to get a glimpse into past minds behind material remains, which is one of the central goals of archaeology. Information theoretic measures, similar to those presented in this work, could be useful for testing different hypotheses about the structure of symbolic systems. Incorporating these interdisciplinary methods into numismatic research could advance the studies on diffusion and transmission of coin motifs and further our understanding of the forces and meaning behind these patterns, improve the techniques of coin recognition, as well as help with reconstruction of coin production and weight standards.

Working with historical objects is challenging and requires a substantial level of expertise. Collaborative interdisciplinary research, combining large- and small-scale studies, synchronic and diachronic approaches, and traditional and novel methodologies is indispensable for a holistic approach to human history. Increasing focus on digitization of historical sources and various types of archaeological data and developing standardized formats for representing cultural items made these data more accessible to the wider scientific community. Archaeologists and historians have embraced the possibilities offered by the computational approaches and statistics, but many are still sceptical of quantifying culture. This scepticism is often justified, in response to the trend of hunting for patterns in big datasets and offering unfounded explanations for cultural phenomena. However, computational approaches to culture based on the theory of cultural evolution and information theory have much to offer to research in humanities and social sciences.

Appendix 1

Supplementary material for the paper "Ancient coin designs encoded increasing amounts of economic information over centuries"

This supplementary material provides additional information on our methodology (section 0), as well as an exhaustive summary of all our work on this topic, including two preregistered pilot studies.

The first study (section 1), preregistered on the Open Science Framework (OSF) on 20/11/2017 (https://osf.io/v8k64), used a dataset of coins issued by Greek city-states between c. 625 and 336 BCE. We preregistered and tested three predictions, based on the assumption that the increased political and commercial interaction between the Greek city-states in the period when the coins first appeared would influence the role of coin designs as markers of state authority and economic value. Our first analysis was mistaken in many respects (listed in section 1.3). This document presents a reanalysis where the format of the dataset, binning and analyses correspond to the analyses carried out in the two subsequent studies. The original preregistration (Appendix 1, online) is included in the online repository (see section 0.1) and, for full disclosure, we also publish our initial (inaccurate) analyses (Appendix 2, online), since they informed the next studies.

The second study (section 2) was preregistered on the 28/03/2018 (https://osf.io/bcrgu), after the first (erroneous) analysis had been done for Study 1. The preregistration document is given in Appendix 3 (online). New predictions were made, informed by earlier results. We used an entirely different dataset, covering a broader time span (from c. 580 to 31 BCE) and including more coin types. This study was focused on the evolution of the value-relevant information encoded in coin designs. The results were substantially similar to those of the paper.

The third study (section 3) is the one described in our paper. Since the second study confirmed the findings of the first one, we decided to combine the two datasets and test all the predictions registered in each of the previous studies on the combined dataset. This document summarizes its main results, and adds information about bin sizes.

0. Supplementary methods

0.1. Data and R code

We provide the relevant dataset and R code for each of the studies in the online repository (https://osf.io/tkv67/?view_only=65bc6dbcc69c49308491598a95f15c6b). Each folder contains a *readme.txt* file explaining the contents of the folder as well as the variables of the dataset, and the structure of the R code. The datasets are appended in two formats: the reformatted dataset, describing each coin with its issuing authority, denomination and design names ("dataset" in a table below), and the R-code input file, where the key variables are recoded using numerical codes assigned to alphabetically arranged authority, denomination and design names (**Table 1**).

folder	R code	input file	dataset
STUDY 1	sng_code.R	sng.csv	sng_names.csv
STUDY 2	mantis_code.R	mantis.csv	mantis_names.csv
STUDY 3	coins_code.R	coins.csv	coins_names.csv

Table 1. The content of our open data and R code folders.

0.2. Statistical software and standard abbreviations

All statistics were computed using R. All entropy calculations were calculated using the *infotheo* package for R (Meyer, 2014). Linear mixed effects models were computed with *lmerTest* (Kuznetsova et al., 2017). The equations corresponding to our various entropy measures are given in the main paper, Methods section. When comparing linear mixed effects model, we used Akaike's Information Criterion (abbreviated as AIC). "95% confidence interval" is abbreviated as "95% CI". All reported p-values in all three studies are two-tailed.

0.3. A short lexicon

Authority: An official entity responsible for issuing coins. Most often a state, but coins could also be issued in the name of a ruler or a dynasty.

Coin type: A category of coins, defined as all the individual coins sharing the same design, the same issuing authority, the same denomination, and the same date. Sometimes we abbreviate this as "coin".

Denomination: A coin's face value, expressed in standardized monetary units (drachma, stater, etc.).

Design: The set of all images minted on both the obverse and reverse side of an individual coin. Note that in numismatics, the term "coin type" is used to refer to the central motif struck on either side of a coin (an "obverse type" or a "reverse type"). We do not use that word in this sense (see "coin type" above).

Individual coin: A single object; a metallic disk bearing a design. Not to be confounded with a coin type.

Motif: An individual image forming part of a coin's design, usually part of a standardized graphical repertoire (animals, gods, heroes, plants, monsters, historical characters, abstract symbols, etc.).

0.4. Data processing

Denominations. Our sources already list each individual coin's denomination in a standardized fashion, so we did not reformat this data. Denominations were encoded and considered as categorical variables, not as quantities of monetary values. Value calculations only played a role when binning the coins according to their value.

Motifs and designs. Coin designs were coded in two steps. First, we made a list of all the individual motifs carried by each coin in the database. We focused on individual human figures, animals, plants, objects, and symbols, excluding inscriptions (monograms, personal names and place names). We did not include detailed features such as the posture of a depicted person or animal, their age, clothing, or hairstyle. Also, we disregarded the motifs that rarely appear independently and are either more likely to appear as attributes with a particular character (e.g., Herakles' lion skin), or are a part of the character's clothing (e.g., headband, jewellery, military dress, hats, staffs, etc.). The variants of the same motif, e.g., different kinds of helmets, stars, etc. were coded as simple instances of the basic motif (e.g., a helmet, a star). 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. For instance, three dolphins, four dolphins and one dolphin would each be coded as one occurrence of the "dolphin" motif. The orthographic and terminological variants of authority, denomination and motif names were standardized (**Figure 1**). Next, we created the variable "design" by merging all the motifs of a coin type into a single alphabetically arranged string. We also calculated the number of motifs composing a coin design. At the end, we assigned arbitrary numerical codes to authorities, denominations and designs.

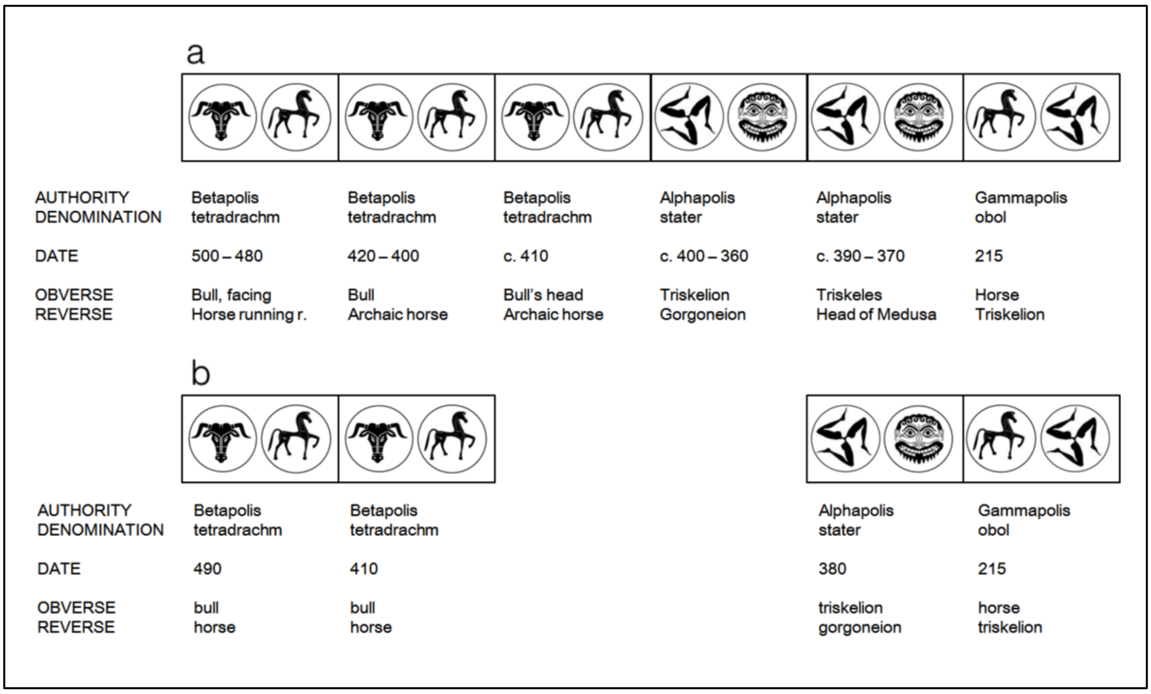

Figure 1. How we reformatted the raw data (coin descriptions from the various datasets): A stylized example. In the first row (a), a set of coins resembling the raw data. In (b), what these coins would look like after treatment. The dates were coerced, when necessary, to the median date of the interval. The motif descriptions were standardized. Duplicates–the 2 coins in the middle in (a)–were removed.

Dates. Our sources usually date individual coins by time intervals (in years BCE). All dates were coerced to one date, the median year of the time interval.

Removing duplicates; other exclusions. We kept only unique coin types (coins of a certain denomination, issued by a certain authority in a certain time period, bearing a given design), and eliminated all duplicate tokens of the same coin type. The coin types lacking information on their issuing authority, denomination or design were excluded. We also excluded objects that are not coins in the usual sense of the word, but cast bronze objects used as currency in Eastern Greek colonies (Mielczarek, 2005). Also discarded were all inconsistent entries and coins missing key information on issuing authority, denomination and coin design. Since duplicates were removed, each remaining single coin in our dataset stands for one distinct coin type.

Data binning. Our entropy measures cannot be computed over single coin types. They require the coins to be binned into groups of several coins. Depending on the analyses, we binned the coins in several ways.

Time bins. Some time periods are over-documented by our data relative to others, leading to possible biases. We used an unsupervised discretization algorithm (*discretize* function of the *infotheo* package) to create time bins containing roughly similar quantities of coins (**Figure 2**.).

Time-authority bins. Time-authority bins were obtained by splitting the time bins according to each coin's issuing authority.

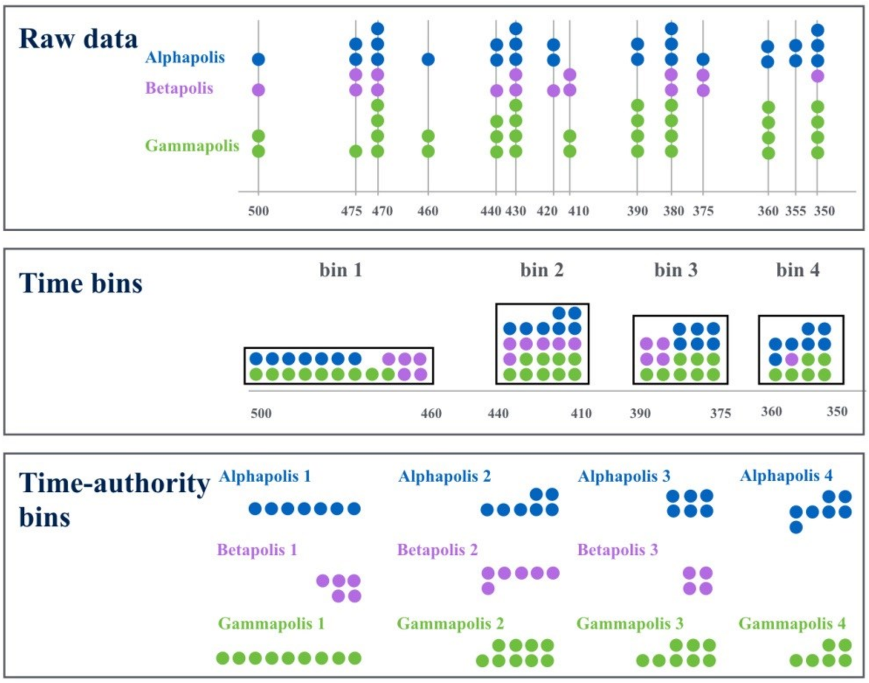

Figure 2. How we binned coins into time bins: a stylized example. We used an unsupervised discretization algorithm to sort the raw data (top row) into discretized bins (middle row). We then split these bins according to the coins' issuing authorities to get time-authority bins.

Value bins. Value bins were created by binning coins according to their value. We had to identify the "base value" of the currency for each denomination, and determine the "relational" value of each denomination, with respect to this base value. A 10 euro cent would have a relational value of 0.1 in respect to the base value of its currency–1 euro. We simplified the complex Greek denomination systems by identifying four base values: the Persian daric, the eastern Greek stater, the mainland Greek drachma and the south Italian litra. The value of each coin was expressed in relation to one these four bases, depending on which system the coin was part of. These calculations were based on the information available in the literature, in conjunction with the information present in the database (Head, 1911; Kraay, 1976; Sayles, 2007; VanHorn and Nelson, 2009). All the coins whose denomination was higher than the base value (one drachma, one litra, one stater, one daric, depending on the system) were deemed to be high-value coins. All the coins whose denomination was strictly lower than their system's base value were discarded. Coins whose denomination equalled the base value were discarded (**Figure 3**).

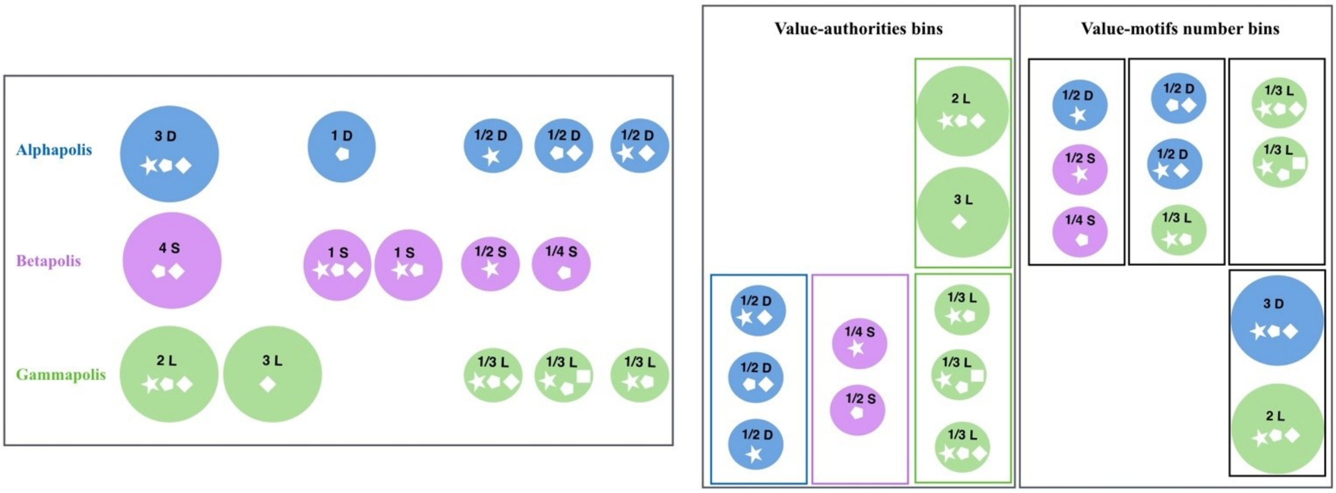

Figure 3. How we binned the coins according to their value: a stylized example. Each coin's value was assigned relatively to the basic unit of its currency system (D = drachma, S = stater, L = litra). All coins higher than one basic unit were binned as high-value, all coins lower than the unit were binned as low-value. Depending on the analysis, we split these two sets according to the coins' issuing authority (value-authority bins), or to the number of motifs included on a coin's design (value-motifs number bins). Note the exclusion of all bins that would contain only one coin.

Value-authority bins. These bins were created by splitting the two value bins according to each coin's issuing authority.

Value-motif number bins. These bins were created by splitting the two value bins according to the number of motif present on each coin's design

1. Study 1: The *SNG* dataset (c. 625–336 BCE)

1.1. Summary

Our first study on the informational value of Ancient Greek coins was preregistered on the Open Science Framework on 20/11/2017 (see Appendix 1 online). Before looking at the data, we hypothesized that increased political and commercial interaction between the Greek city-states in the period when coins first appeared and spread thorough the Ancient Mediterranean would influence the role of coin designs as markers of both state authority and economic value. We made three predictions: the cultural transmission of coin designs between city-states would bring about a decrease of the coins' informational value about their issuing authorities with time. On the other hand, economic integration would increase the pressure for clearly signalling a coin's exchange value, increasing the informational value of coin designs concerning a coin's denomination. We also predicted that the designs on small change coins (lower denominations) would carry more value-relevant information than the ones on higher denomination coins, because more informative designs could potentially compensate for frequent errors in the production of smaller coins.

We used a dataset of coins issued by Greek city-states from the invention of coinage in the last quarter of 7th century BCE, until the beginning of Alexander the Great's rule in 336 BCE, to test three predictions concerning the evolution of the informational value of coin designs. We originally planned to bin the coins into three time bins corresponding to the 6th, 5th, and 4th century BCE, but to be consistent with other studies, this report uses both these time bins and the time bins produced by the unsupervised discretization algorithm.

We found that the value-relevant information encoded in coin designs did increase with time, as predicted, but only weakly. We also found, contrary to our prediction, that state-relevant information also tended to increase (weakly). When testing for differences between the amount of value-relevant information on coins of higher or lower denomination, we found the opposite of our expectation to be true: the coin designs of higher denomination coins carried more value-relevant information than the designs coin designs of lower denomination coins. This effect was strong and significant, and proved robust when controlling for baseline denominations entropy or design complexity (defined as the number of motifs on a coin's design).

This report replaces and supersedes our first report on Study 1 (Appendix 2 online), whose analysis was flawed in several respects (see section 1.3).

1.2. Table of results

Does state-relevant information decrease through time?	**Time-bins:** 11 bins, 1548 coins	**Conditional Entropy (CE):** H(authorities | designs)	Negative Spearman's ρ = -0.246.
		Normalized CE: H(authorities | designs) / H(authorities)	Negative Spearman's ρ = -0.228.
Does value-relevant information increase through time?	**Time-bins:** 11 bins, 1548 coins	**Conditional Entropy (CE):** H(denominations | designs)	Negative Spearman's ρ = -0.364.
		Normalized CE: H(denominations | designs) / H(denominations)	Negative Spearman's ρ = -0.418.
	Time-authority bins: 1548 coins, 183 states, 11 time-bins, 451 Time-authority bins	**Conditional Entropy (CE):** H(denominations | designs)	Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor. AIC = 29.4, inferior to the AIC of the null model without DATE (30.6). Negative estimate for DATE: β = - 0.0003; SE = 0.0002; t-value = -1.798.
		Normalized CE: H(denominations | designs) / H(denominations)	Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor. AIC = 143.09, superior to the AIC of the null model without DATE (142.93). Negative estimate for DATE: β = - 0.0006; SE = 0.0004; t-value = -1.364.
Is value-relevant information greater on low-value coins?	**Value-authority bins:** 891 coins (561 low-value coins; 330 high-value coins) 136 value-authority bins (65 high-value bins, 71 low-value bins)	**Conditional Entropy (CE):** H(denominations | designs)	Wilcoxon's rank sum test: Designs are more informative for high-value coins: (W = 1797**)
		Normalized CE: H(denominations | designs) / H(denominations)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 1807**)
	Value-motifs number bins: 962 coins (379 low-value coins; 583 high-value coins) 17 bins (11 high-value bins 6 low-value bins)	**Conditional Entropy (CE):** H(denominations | designs)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 15*)
		Normalized CE: H(denominations | designs) / H(denominations)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 16)

Table 2. The predictions and results of Study 1. The results coloured in red are inconsistent with our predictions. Results coloured in green are consistent. P value symbols: *: p <.05, **: p<.01.

1.3. Problems with the previous analysis

Our original analysis, published in a report on 05/03/2018 (Appendix 2, accessible on the online repository), was flawed in several respects. The main problem was the formatting of the dataset, which was ill-suited for measuring the informative value via conditional entropy with *infotheo*. We subsequently discovered that the *infotheo* functions treat the values as types, not tokens, which meant our dataset had to be reformatted, and the analyses repeated.

The second problem had to do with the way we binned of the dates provided for the coin types by our database into more manageable time periods. The pre-registration had planned to bin the coin types by century (6^{th}, 5^{th}, or 4^{th} century BCE). We realized this was an inconvenient way of binning the data, because of the great imbalance in the number of coin types between the three centuries. For the next studies we decided to use the *discretize* function of the *infotheo* package to create homogeneous time-bins. Here, we report both the results based on the pre-registered 3-centuries bins, and the repeated analysis using discretized bins. The statistical analyses are performed with the discretized bins only.

The third problem was due to a failure to eliminate some duplicate coins (coins sharing the same issuing authority, date, and design).

Lastly, because our preregistered predictions did not precisely specify whether the "coin motifs" referred to the individual motifs (e.g., an owl), or full designs composed of one or more motifs (e.g., an owl and an olive branch), we were supposed to carry out our analyses considering both individual motifs and full designs. However, the vast majority of single motifs is not documented by a sufficient number of coins for us to run our preregistered measure on the data and get a meaningful result. We thus decided to focus, here and in all the following studies, on the information carried by whole designs – the complete images present on both sides of a coin.

Given these problems, our previous report shouldn't be considered valid. This report is the final and valid version.

1.4. Data processing

The dataset was assembled from the online database of the *Sylloge Nummorum Graecorum* (*SNG*) project of the British Academy (Carradice and Popescu, n.d.). The online database contains c. 25 000 coins from the 13 published volumes of the *SNG* project's catalogues of Greek coins, gathered from public and private British collections. In this first study, we focused on the Archaic and Classical periods. We searched the database for all coins dated before our chosen end-year, 336 BCE (the year of Alexander the Great's ascension, which in numismatics marks the beginning of the Hellenistic period – Head, 1911, p. lxii ff.).

Issuing authorities. To determine each coin's issuing authority, we combined information on the issuing state, mint and ruler in the following way: the information on the issuing state (e.g., Corinth, Athens) was prioritized, but if missing, it was replaced by the information on the mint, or in case both state and mint were missing, we took the name of the ruler.

Exclusions. After application of our exclusion criteria (see section 0.4), we retained 1548 unique coin types from the initial 3584 individual coins.

Discretization into date bins. The algorithm was run over our set of 1548 coins, after each coin's date was formatted. This yielded 11 time-bins (**Table 3**).

Normalized date	period BCE	n coin types
0	625-508	91
72	500-488	172
92	485-464	105
108	463-454	67
126	450-430	258
146	425-415	69
158	413-404	187
174	400-385	149
194	380-365	144
214	363-341	164
228	338	142

Table 3. The 11 time-bins of Study 1. The normalized date (first column) was the one used in our analyses. The approximate interval of time in years BCE covered by each bin is given in the second column, the number of coin types in the last column.

1.5. Results

1.5.1. Does state-relevant information decrease through time?

We computed the conditional entropy of authorities given designs, for each of our 11 time-bins. The results show a non-significant decrease in conditional entropy with time (Spearman's rho = -0.246, p = 0.466). In order to control for the variance in the basic entropy of authorities, we computed the normalized conditional entropy, H(authorities|designs) / H(authorities). Here we again found a decrease of conditional entropy with time, still not significant (Spearman's rho = -0. 228, p = 0.501). The same analysis performed on the 3 century-bins, as preregistered, did not produce any noticeable trend. This weak decrease in conditional entropy means that state-relevant information slightly increased during that period, contrary to our prediction (**Figure 4**).

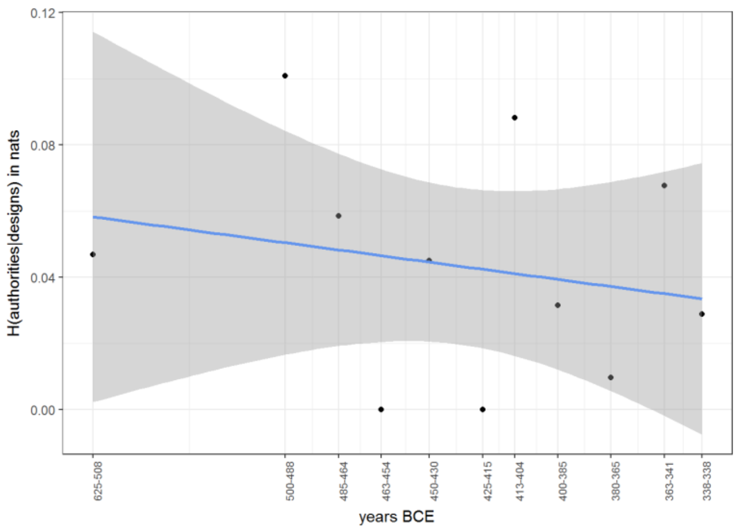

Figure 4. The state-relevant information carried by coins of the *SNG* corpus (c. 625–336 BCE), computed as the conditional entropy of authorities given designs. The grey area marks the 95% CI.

1.5.2. Does value-relevant information increase through time?

Here as in the two other studies, this prediction was tested in two distinct ways: with time-bins and with time-authority bins.

Simple time-bins. We computed the conditional entropy of denominations given designs as well as the normalized conditional entropy H(denominations|designs) / H(denominations) for each of the 11 time-bins. A negative Spearman’s rho suggested a decrease in both non-normalized (Spearman's rho = -0.364, p = 0.273) and normalized conditional entropy

(Spearman's rho = -0.418, p = 0.203) with time. However, the result was not statistically significant. Repeating this analysis on the three pre-registered century-bins did not produce any trend.

Time-authority bins, distinguishing coins by issuing states. Testing our hypothesis on Time-authority bins is necessary to avoid giving greater weight to the states that issue a vast number of coins. We built a linear mixed effects model using as the dependent variable the conditional entropy of denominations given designs for each Time-authority bin (n = 451 bins). We included the issuing authority for each bin as random effect. This null model was compared with another model, identical to the null model but adding each bin's DATE as predictor. Model comparison showed that the model with the predictor had a lower AIC score (29.459) than the null model (30.680), which suggests that the predictor did improve the model. The predictor DATE had a non-significant negative estimate (β = -0.0003; SE = 0.0002; t-value = -1.798; p = 0.0729), meaning that the conditional entropy of denominations given designs shows an unclear decrease with time. A decrease means that the information carried by coin designs becomes increasingly value-relevant (**Figure 5**).

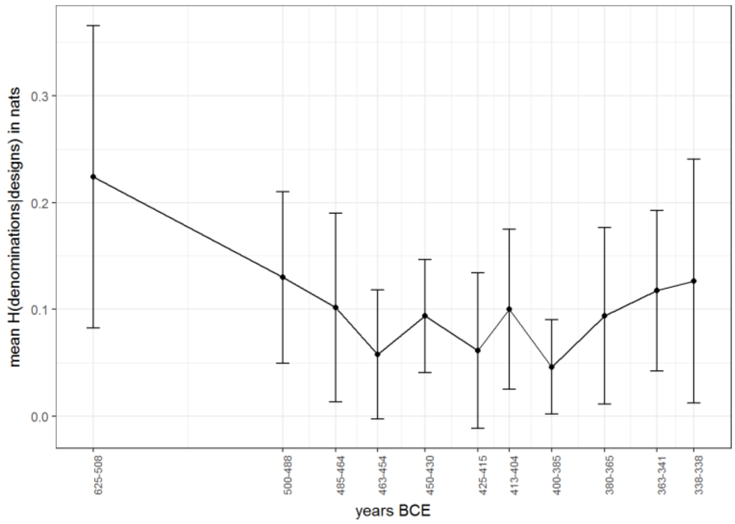

Figure 5. The value-relevant information carried by coins of the *SNG* corpus (c. 625–336 BCE), computed as the conditional entropy of denominations given designs, measured across authorities for each time bin. The time bins are labelled chronologically as intervals of years BCE. The black dots represent the mean informational value, averaged across authorities, for each period. Error bars = 95% CI.

To control for baseline variations in the entropy of denominations, we repeated this test with normalized conditional entropy, H(denominations|designs) / H(denominations), instead of entropy. This substantially weakened the observed trend: this time the AIC score for the model with predictor (143.09) was slightly higher than the AIC of the null model (142.93), and the estimate for the effect of DATE was no longer significant (β = -0.0005; SE = 0.0004; t-value = -1.364; p = 0.17).

1.5.3. Is value-relevant information greater for lower-value coins?

We predicted that the designs on low-value coins would be more informative about the coins' denominations than the designs on high-value coins: the conditional entropy of denominations given designs would be lower for low-value coins. We binned our dataset into two bins, one high-value, one low-value (see above, section 0.4). The "high-value" bin comprised 583 coin types with a relational value larger than 1, and the "low-value" bin 380 coin types with a relational value smaller than 1. All coin types with a relational value of 1 (equal to the base value, n = 585) were excluded from the analyses. Starting from this, we tested our prediction on two types of bins.

Coins binned by values and by states. Each of our two bins, the Low-value and the High-value bins, were further binned according to each coin's issuing state. This resulted in 65 higher denominations bins (561 coins in total) and 71 lower denominations bins (330 coins in total). A nested regression was not suitable to test our prediction, due to the structure of the data: the proportion of the variance accounted for by the nesting variable (authority) could not be estimated due to the scarcity of different data points per authority. Therefore, in order to compare the values in the two bins, we used a two-sided Wilcoxon's rank sum test. The results showed the opposite from what we expected: the tests for both non-normalized and normalized conditional entropy suggested that the higher denominations actually had a lower entropy than the lower denominations, meaning that their designs carry more value-relevant information (W coefficient = 1797, p = 0.001 for conditional entropy; W = 1807, p = 0.001 for normalized conditional entropy) (**Figure 6.**).

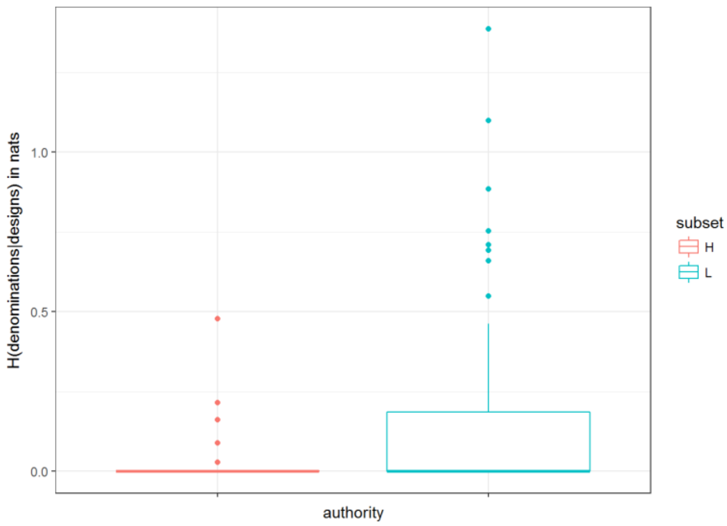

Figure 6. Value-relevant information in the designs of high- and low-value coins from the *SNG* corpus, measured as the conditional entropy of denominations given designs, for each of the two subsets: higher denominations (in red, n subsets = 65, n coin types = 561) and lower denominations (in blue, n subsets = 71, n coin types = 330). The boxes encompass the first to third quartiles; horizontal lines indicate median values, and the dots indicate the outliers.

Coins binned by values and by number of motifs. Having obtained this unexpected result, we carried out an additional test in order to control for the possibility that the greater quantity of information carried by designs on higher denomination coins could be due to the generally larger size of the higher denomination coins, which could accommodate more complicated and diverse designs composed of a greater number of individual motifs. In order to test this, we again measured the conditional entropy H(denominations|designs) and normalized conditional entropy H(denominations|designs) / H(denominations) separately for higher and lower denominations subsets, this time across value-motif number bins. Again, the structure of the data was not suitable for a test with nested linear regression because of the small number of data points per number of motifs, and we instead ran Wilcoxon's rank sum test, which confirmed the finding of the main test (**Figure 7**): the designs on high-value coins have more value-relevant information than the designs of low-value coins (W coefficient = 15, p = 0.049 for conditional entropy, W = 16, p = 0.063, for normalized conditional entropy).

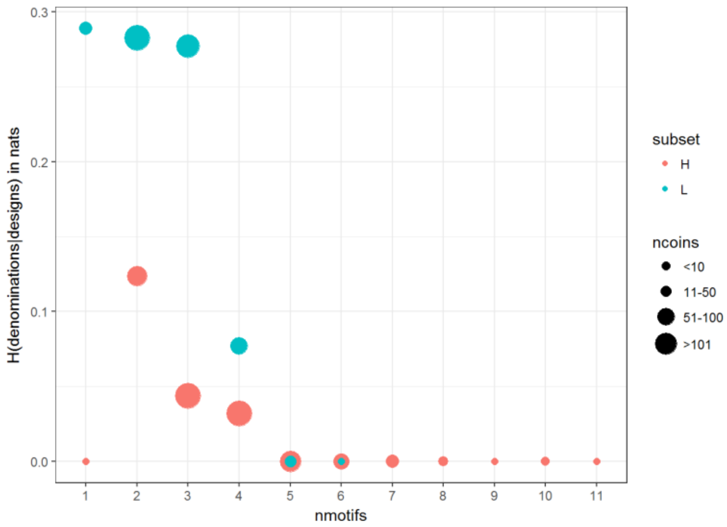

Figure 7. Value-relevant information in the designs of high- and low-value coins from the *SNG* corpus, measured as the conditional entropy of denominations given designs, depending on the coins' value and on the number of motifs on their design. Higher denominations in red (n subsets = 11, n coin types = 583), lower denominations in blue (n subsets = 6, n coin types = 379). The size of the dots indicates the number of unique coin types in each subset (total n = 891).

2. Study 2: The *MANTIS* dataset (c. 580–32 BCE)

2.1. Summary

This second study, preregistered on 28/03/2018 (Appendix 3, online), focused on the evolution of the value-relevant information carried by coin designs. This time, we expanded the chronological range of our analysis to include Hellenistic coins produced during and after the conquests of Alexander the Great, who introduced the coinage of standardized designs and denominations to the vast areas of the ancient East, where they gradually replaced the local city-state coinage (Meadows, 2014; cf. Howgego, 1995, p. 22; Rutter, 1983, p. 16). Our time range extended as far as the Roman conquest of Greece (31 BCE).

We again predicted an increase of value-relevant information with time, but we also tested whether the coin designs become more organized in order to reflect the denominational structure, predicting that the increasingly standardized denominational structure of Hellenistic coinage would be reflected in the informational value of the coin designs. Lastly, we predicted that we would replicate, on a different dataset, the finding of Study 1: higher denominations would carry more value-relevant information than the designs on lower denominations. (Unlike the others, this prediction was not theory-driven, but directly suggested by our previous finding.)

As in Study 1, we found that ancient states, on average, increased the value-relevant content of their coin designs over time. We did not find that the designs became more organized in order to reflect the denominational structure. In line with Study 1, we found that the coin designs on higher denominations carried more value-relevant information than the designs on lower denominations, although this result was not necessarily robust when controlling for the number of motifs on a coin.

2.2. Table of results

Does value-relevant information increase through time?	**Time-bins:** 17 bins, 5375 coins	**Conditional Entropy (CE):** H(authorities | designs)	Negative Spearman's ρ= - 0.270
		Normalized CE: H(authorities | designs) / H(authorities)	Positive Spearman's ρ= +0.005
	Time-authority bins: 5375 coins 571 states 17 time-bins 1230 Time-authority bins	**Conditional Entropy (CE):** H(denominations | designs)	Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor. AIC = 484, inferior to the AIC of the null model without DATE (507). Negative estimate for DATE: β = - 0.0003 ; SE = 0.0001; t-value = -4.996**
		Normalized CE: H(denominations | designs) / H(denominations)	Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor. AIC = 433, inferior to the AIC of the null model without DATE (438). Negative estimate for DATE: β = - 0.0003; SE = 0.0001; t-value = -2.776**
Do designs become organized according to denominations over time?	**Time-authority bins:** 5375 coins 571 states 17 time-bins 1230 Time-authority bins	**Conditional Entropy (CE):** H(designs | denominations)	Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor. AIC = 1737.9, superior to the AIC of the null model without DATE (1737.5). Negative estimate for DATE: β = -0.0001; SE = 0.0001 ; t-value = -1.262.
Is value-relevant information greater on higher denomination coins?	**Value-state bins:** 3520 coins (1599 low-value coins; 1921 high-value coins) 208 high-value bins, 194 low-value bins	**Conditional Entropy (CE):** H(denominations | designs)	Wilcoxon's rank sum test: Designs are more informative for high-value coins: (W = 12124**)
		Normalized CE: H(denominations | designs) / H(denominations)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 12970**)
	Value-motif number bins: 3777 coins (2059 low-value coins; 1718 high-value coins) 11 high-value bins 10 low-value bins	**Conditional Entropy (CE):** H(denominations | designs)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 19*)
		Normalized CE: H(denominations | designs) / H(denominations)	Wilcoxon's rank sum test: Designs are more informative for high-value coins (W = 35)

Table 4. The predictions and results of Study 2. The results coloured in red are inconsistent with our predictions. Results coloured in green are consistent. P value symbols: *: p <.05, **: p<.01.

2.3. Data processing

We used the coins described in the *MANTIS* online database of the American Numismatic Society (American Numismatic Society, 2015), listed in the “Greek department”. The database includes more than 92 000 coins, from the early 7th century electrum coins to the coinage struck under Roman rule until the 3rd century CE, in mainland Greek city-states, colonies in the West and the East and other Hellenized ancient Mediterranean civilizations, which adopted the Greek invention, except Rome. We started by including all the coins dated between the 7th century and 31 BCE, and proceeded to adapt the dataset to fit the needs of the study. The data points lacking key information (any of the *MANTIS* variables “Authority”, “Mint”, “Dynasty”, “Issuer”, “Region”, “Denomination”, “Obverse Type” and “Reverse Type”) were excluded from the dataset. To determine a coin’s issuing authority, we used the information on the issuing authority, when available. Lacking that, we took the mint if it was mentioned, otherwise the dynasty, then the issuer, and lastly, the region. In all other respects, our methods were identical to those described in section 0.4. This left us with 5375 unique coin types, covering the period between c. 580 and c. 32 BCE, binned into 17 time bins (**Table 5**).

Normalized date	period BCE	n coin types
0	580-513	309
46	510-491	291
69	490-465	347
96	464-436	311
128	435-402	325
160	401-372	313
188	370-347	315
212	345-325	304
232	324-305	331
251	304-287	310
278	286-250	317
314	249-215	316
348	214-182	310
379	181-154	316
406	153-128	318
437	127-92	321
485	91-32	321

Table 5. The 17 time-bins of Study 2. The normalized date (first column) was the one used in our analyses. The approximate interval of time in years BCE covered by each bin is given in the second column, the number of coin types in the last column.

2.4. Results

2.4.1. Does value-relevant information increase through time?

This prediction was tested over two kinds of time bins, as in Study 1.

Simple time-bins, not distinguishing states. We computed the conditional entropy of denominations given designs, H(denominations|designs), as well as the normalized conditional entropy H(denominations|designs) / H(denominations), for each of the 11 time-bins. A negative Spearman's rho suggested a weak decrease in non-normalized conditional entropy (Spearman's rho = -0.270, p = 0.29), but not its non-normalized counterpart (Spearman's rho = 0.005, p = 0.98).

Time-authority bins, distinguishing coins by issuing states. Testing our hypothesis on Time-authority bins is necessary to avoid giving greater weight to the states that issue a vast number of coins. We built a linear mixed effects model using as the dependent variable the conditional entropy of denominations given designs for each time-authority bin (n = 1230 bins). We included the issuing authority for each bin as random effect. This null model was compared with another model, identical to the null model but adding each bin's DATE as predictor. Model comparison showed that the model with the predictor had a lower AIC score (484) than the null model (507), which suggests that the predictor did improve the model. The model gave for the effect of DATE a significant negative estimate ($\beta = -0.0003$; SE = 0.0001; t-value = -4.996; $p < 0.0001$), meaning that the conditional entropy of denominations given designs shows a clear decrease with time: the information carried by coin designs became increasingly value-relevant (**Figure 8**). To control for the influence of baseline variations in the entropy of denominations, we repeated this test with normalized conditional entropy, H(denominations|designs) / H(denominations), instead of entropy. The results were similar. The AIC score for the model with DATE was lower than the AIC of the null model (433 vs. 438), and the estimate for the effect of DATE was negative and significant ($\beta = -0.0003$; SE = 0.0001, t-value = -2.776; $p = 0.0057$).

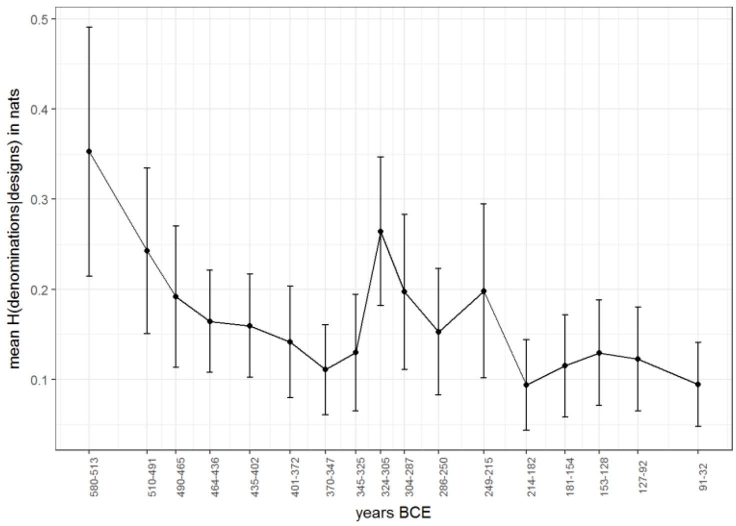

Figure 8. The value-relevant information carried by coins of the *MANTIS* corpus (c. 580–31 BCE), computed as the conditional entropy of denominations given designs, measured across authorities for each time bin. The time bins are labelled chronologically as intervals of years BCE. The black dots represent the mean conditional entropy, averaged across authorities, for each period (error bars = 95% CI).

2.4.2. Do designs become better organized to reflect denominations?

The result we just showed – coin designs carry more and more value-relevant information as time goes by – admits of two distinct explanations. The information increase could be due to a diversification of coin designs. States could mint more varied images for each denomination. Here, we tested a second possibility: that coin designs were being used in a more consistent fashion – the same designs being used for the same denominations by different states. This would lead to a decrease in the conditional entropy of designs given denominations, H(designs|denominations). We tested this hypothesis only with the non-normalized conditional entropy: baseline variations in the entropy of designs were an important part of the dynamic we wanted to capture, and not something to be controlled for in this instance. The analysis used the same data as the previous tests. Only the measure differed: H(designs|denominations) instead of H(denominations|designs). The nested linear regression carried out over 1230 date-state bins gave a negative estimate for the effect of DATE ($\beta = -0.0001$; SE = 0.0001; t-value = -1.262; $p = 0.207$) (**Figure 9**). However, the AIC score of the model with the predictor was higher (1737.9) than the AIC score of the null model (1737.5), meaning that the predictor did not improve the model. We therefore cannot consider this prediction confirmed.

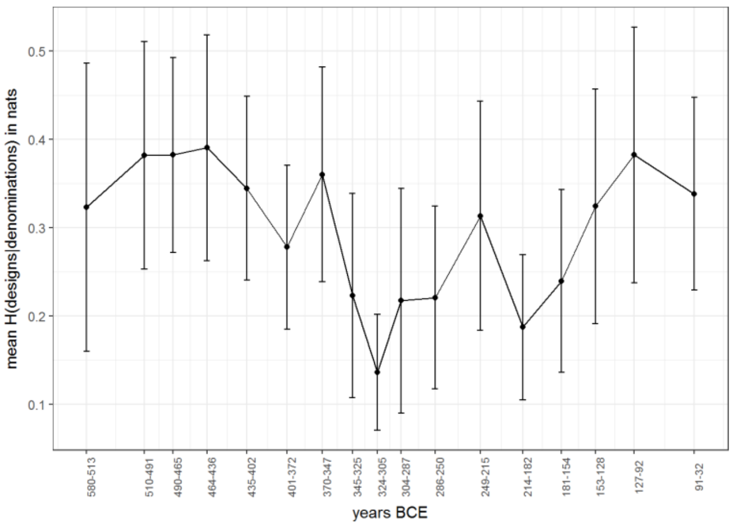

Figure 9. The degree to which coin designs were organized to correspond to the coins' denominations, measured for the *MANTIS* corpus as the mean conditional entropy of designs given denominations, measured across the coin types issued by different authorities, for our 17 date bins. Error bars = 95% CIs.

2.4.3. Is value-relevant information greater for higher denominations?

Based on our previous results, we predicted that the designs on high-value coins would carry more value-relevant information than the designs on low-value coins: the conditional entropy of denominations given designs would thus be higher for low-value coins. We binned our dataset into two bins, one high-value, one low-value, according to the value of each coin's denomination, relative to the base value of the respective denominational system (see above, section 0.4). The "high-value" bin comprised 2061 coin types with a relational value larger than 1, and the "low-value" bin 1718 coin types with a relational value smaller than 1. All coin types with a relational value of 1 (equal to the base value, n = 1596) were excluded from the analyses. Starting from this, we tested our prediction in two distinct ways, as we had done for Study 1.

Value-state bins. Each of our two bins, the Low-value and the High-value bins, were further binned according to each coin's issuing state. All the resulting bins containing only 1 coin were excluded. This resulted in 208 higher denominations subsets (1921 higher denominations coin types issued by 208 different authorities), and 194 lower denominations subsets (1599 lower denominations coin types issued by 194 different authorities). We replicated Study 1's result. The designs of higher denomination coins seem to encode more value-relevant information than those of low-value coins. In other words, the conditional entropy of denominations given designs is lower for high-value coins (W coefficient = 12124 for simple conditional entropy, $p < 0.0001$; 12970 for normalized conditional entropy, $p < 0.0001$).

Value-motif number bins. We carried out an additional test, to verify that the presence of designs with more value-relevant information on higher denomination coin types is not caused by the fact that the larger size of higher denomination coins could more easily accommodate a larger number of individual motifs, making for more diverse designs. Here we measured the conditional entropy H(denominations|designs) and the normalized conditional entropy H(denominations|designs) / H(denominations) for the subsets of coin types carrying the same number of individual motifs, inside the higher and lower denomination subset separately, excluding the subsets containing only one coin type. We computed the values for 11 higher denominations subsets (for a total of 2059 coin types) and 10 lower denominations subsets (for a total of 1718 coin types). Wilcoxon's rank sum test confirmed the previous finding (see **Figure 10**): higher denomination coin designs carry more value-relevant information, regardless of the number of motifs composing the designs. The effect was not significant, however, for normalized conditional entropy. (W coefficient = 19, $p = 0.012$ for simple conditional entropy; W = 35 $p = 0.167$, for normalized conditional entropy).

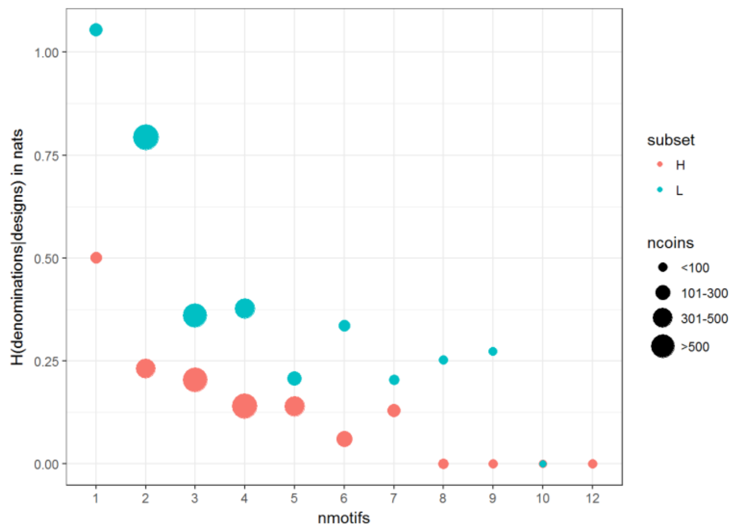

Figure 10. Value-relevant information in the designs of high- and low-value coins from the *MANTIS* corpus, measured as the conditional entropy of denominations given designs, depending on the coins' value and on the number of motifs on their design. Higher denominations in red (11 bins for 2059 coin types), lower denominations in blue (6 bins for 1718 coin types). Dot sizes indicate the number of coins in each bin.

3. Study 3: Pooling the datasets (*SNG* + *MANTIS*, c. 625–31 BCE)

3.1. Summary

This is the study described in the main paper. The results are listed in section 3.2, and discussed in the main paper. We decided to combine the two datasets and test all the predictions on this joined dataset. We did not preregister the third study, since the combined set of all the predictions had already been tested in Study 1, Study 2, or both.

3.2. Table of results

<table>
<tr><td rowspan="2">Does state-relevant information decrease through time?</td><td rowspan="2">Time-bins:
18 bins,
6859 coins</td><td>Conditional Entropy (CE):
H(authorities
| designs)</td><td>Positive Spearman's ρ = + 0. 529*</td></tr>
<tr><td>Normalized CE:
H(authorities |
designs) /
H(authorities)</td><td>Positive Spearman's ρ = + 0. 566*</td></tr>
<tr><td rowspan="4">Does value-relevant information increase through time?</td><td rowspan="2">Time-bins:
18 bins,
6859 coins</td><td>Conditional Entropy (CE):
H(denominations
| designs)</td><td>Positive Spearman's ρ = +0. 036</td></tr>
<tr><td>Normalized CE:
H(denominations |
designs) /
H(denominations)</td><td>Positive Spearman's ρ = +0. 178</td></tr>
<tr><td rowspan="2">Time-authority bins:
6859 coins
601 authorities
18 time bins
1476 Time-authority bins</td><td>Conditional Entropy (CE):
H(denominations
| designs)</td><td>Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor.
AIC = 472, inferior to the AIC of the null model without DATE (485).
Negative estimate for DATE: β = -0.0002; SE = 0.0001;
t-value = -3.942**</td></tr>
<tr><td>Normalized CE:
H(denominations |
designs) /
H(denominations)</td><td>Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor.
AIC = 493, inferior to the AIC of the null model without DATE (496).
Negative estimate for DATE: β = -0.0002; SE = 0.0001;
t-value = -2.292*</td></tr>
<tr><td>Do designs become organized according to denominations over time?</td><td>Time-authority bins:
6859 coins
601 authorities
18 time bins
1476 Time-authority bins</td><td>Conditional Entropy (CE):
H(designs
| denominations)</td><td>Linear mixed model for the CE of Time-authority bins, nested by states, with DATE as predictor.
AIC = 2374.9, superior to the AIC of the null model without DATE (2375.3).
Negative estimate for DATE: β = -0.0001; SE = 0.0001 ; t-value = -1.558.</td></tr>
<tr><td rowspan="4">Is value-relevant information greater on lower denomination coins?</td><td rowspan="2">Value-authority bins:
2485 high-value coins
1966 low-value coins
247 high-value bins,
241 low-value bins</td><td>Conditional Entropy (CE):
H(denominations
| designs)</td><td>Wilcoxon's rank sum test:
Designs are more informative for high-value coins:
(W = 18667**)</td></tr>
<tr><td>Normalized CE:
H(denominations |
designs) /
H(denominations)</td><td>Wilcoxon's rank sum test:
Designs are more informative for high-value coins
(W = 19748**)</td></tr>
<tr><td rowspan="2">Value-motif number bins:
2614 high-value coins 2088 low-value coins
13 high-value bins
10 low-value bins</td><td>Conditional Entropy (CE):
H(denominations
| designs)</td><td>Wilcoxon's rank sum test:
Designs are more informative for high-value coins
(W = 17.5**)</td></tr>
<tr><td>Normalized CE:
H(denominations |
designs) /
H(denominations)</td><td>Wilcoxon's rank sum test:
Designs are more informative for high-value coins
(W = 30.5*)</td></tr>
</table>

Table 6. The predictions and results of Study 3. The results coloured in red are inconsistent with our predictions. Results coloured in green are consistent. P value symbols: *: p <.05, **: p<.01.

3.3. Dataset

We corrected some mistakes in the coding of the original datasets. First, we failed to arrange the motifs in the designs strings in the alphabetical order, which has resulted in a wrong number of unique designs and coin types in the final dataset and might have affected the results. We have corrected this mistake, and we have also corrected mistakes in coding of 17 motifs. This correction was minor and did not affect our results.

Second, we addressed a mistake in coding the AUTHORITY variable, which one of our reviewers pointed out. Originally, we combined several variables from the original databases into our AUTHORITY variable. For the coin types taken from *SNG* database, we combined the information from the *SNG* variables "state" (issuing city-state or region, e.g., Athens or Macedonia), "mint" (a place where a coin was produced), and "ruler" (the monarch in whose name the coins are issued), in that order of priority (see section 1.4). For the coin types obtained from the *MANTIS* database, we combined the information contained in the *MANTIS* variables "authority" (the state or the monarch in whose name the coin was issued, e.g. Corinth, Alexander III), "mint" (a place where a coin was produced), "dynasty" (ruling dynasty; when "authority" is a monarch), "issuer" (a person administratively responsible for the coin issue, mostly a magistrate), and "region" (a geographic or administrative area the coin was issued in), in that order of priority (see section 2.3).

However, the two databases differ in what they treat as the political power behind the production of coinage: while *MANTIS* combines city-states and monarchic rulers in its "authority" variable (e.g., "Corinth", "Alexander III"), *SNG* variable "state" gives priority to city-states and regions (e.g., "Macedon" instead of "Alexander III"). In some cases, merging the variables in the way we have originally done has given unfounded importance to mints as places of production over a state entity that was regulating the production, sometimes at several mints in the same time. We therefore recoded the AUTHORITY variable in the following way:

1. For *SNG*, we combined the information from the *SNG* variables giving priority to the information on the "ruler", if available. Next, we would use the information on "state", and lastly on "mint".

2. For *MANTIS*, we combined the information following the original order of priority (information on "authority", then "mint", followed by "dynasty", "issuer" and "region").

In this way, we have made sure that the state entities are recognized in our dataset as AUTHORITY, as opposed to mints, as our hypothesis is based on the political and economic dynamics between the ancient Mediterranean *states*.

To combine the *SNG*-based and *MANTIS*-based dataset, we harmonized the authority, denomination and motif names between the two datasets, and checked for possible inconsistencies. Further processing has been carried out according to the methods described in section 0.4. We reran the unsupervised discretization algorithm to sort the coin types into 18 balanced "time bins". As usual, duplicated coin types (having the same authority, denomination and design information, and dated into the same "time bin") were excluded them from the dataset. Our finished combined *SNG+MANTIS* dataset contained 6859 coin types, issued by 601 unique authority in 139 unique denominations, carrying 3315 unique designs, and arranged into 18 time bins (**Table 7**). The comparison between the number of designs and authorities or denominations in each period is given in **Figures 11 and 12**, respectively.

Normalized date	period BCE	n coin types
0	625-515	297
68	513-491	451
87	490-476	374
107	475-451	350
127	450-436	403
146	435-414	289
167	413-393	501
188	392-371	369
210	370-351	294
229	350-332	471
246	331-316	392
267	315-291	378
300	290-251	380
340	250-211	386
380	210-171	353
414	170-143	403
450	142-98	386
505	97-33	382

Table 7. The 18 time-bins of Study 3. The normalized date (first column) was the one used in our analyses. The approximate interval of time in years BCE covered by each bin is given in the second column, the number of coin types in the last column.

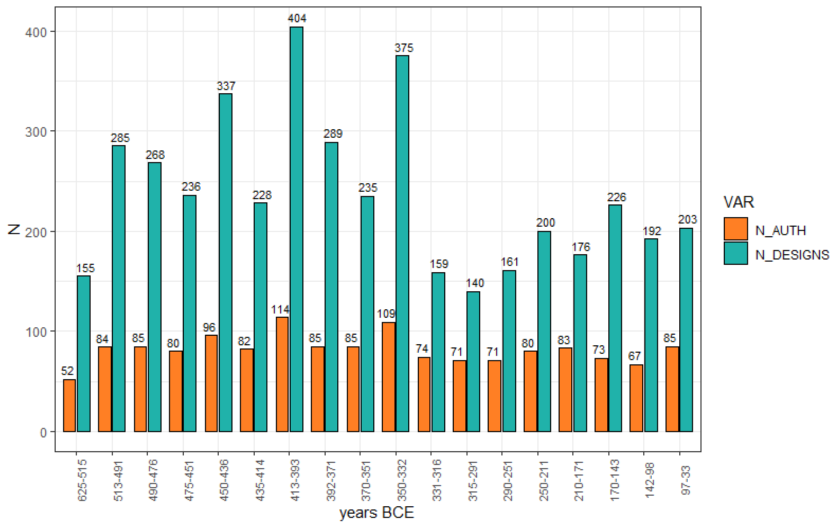

Figure 11. Number of unique authorities (in orange) and designs (in green) through 18 periods.

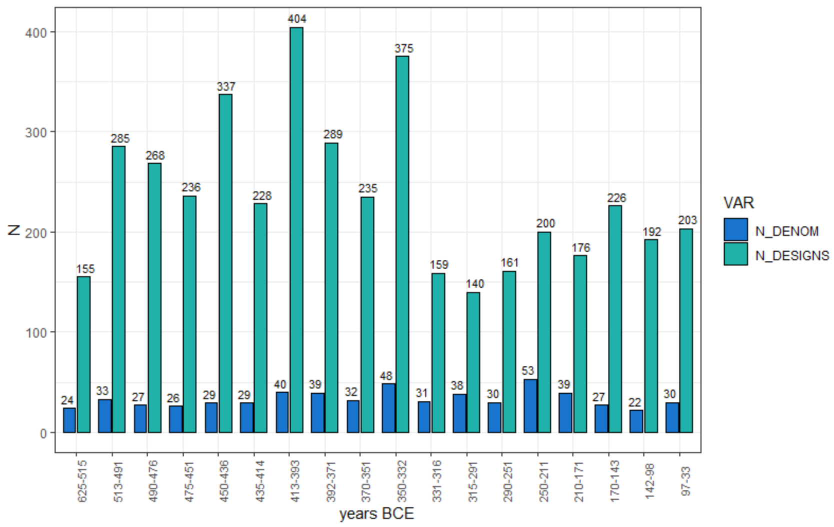

Figure 12. Number of unique denominations (in blue) and designs (in green) through 18 periods.

Appendix 2

Supplementary material for the paper "Reverse engineering cash: Coin designs mark out high value differentials and coin sizes track values logarithmically"

This supplementary material contains the full project documentation for the study reported in the paper *Reverse engineering cash*, including the original study preregistration and report (registered on 25 January 2019 on the Open Science Framework, https://osf.io/ekcdb), as well as the preregistration and report of the additional analyses suggested by the reviewers (registered on the OSF 25 September 2019, https://osf.io/tkj8y). All data and code are available in the following OSF repository:

http://osf.io/2vuba/?view_only=c843d9c30fe24721a1202ccc65fcd7d2.

1. Study preregistration: How do coins encode value: monetary value as an organizing principle of coin properties in contemporary currencies

1.1. Introduction

Currency is a monetary system issued by a government and used as a medium of exchange. It is composed of units of monetary value (denominations), typically a main unit and one or more fractions of the main unit (subunits). Currency denominations are issued as legal tender in form of tokens: coins and banknotes. The structure of a currency is determined by a trade-off between the production costs and efficiency: it should allow the transactions to be carried out with a minimal number of tokens, and the denominations should be conveniently spaced to facilitate the numerical calculations (Bouhdaoui et al., 2011).

Here we are focusing on coins, usually round metal discs bearing a mark of an issuing authority that guarantees their exchange value (design). The coins of different values inside a currency often carry diverse designs and are of different size, colour, thickness and weight. In order for coins to be effective tokens of exchange, the monetary value they represent should be clearly indicated by their physical properties, or their designs.

The euro coins provide a nice example of how different the coins of a single currency can be: although the euro coins are of equal value and size across the Eurozone, each member state chooses their own national designs. Some states, e.g., Estonia, Ireland and Lithuania issue the same design on all coin denominations, whereas others, such as Austria, Greece and Italy have different designs on all of the eight denominations. Most commonly, European states decided to create three different designs (one for 1, 2, 5 cent coins, another for 10, 20, 50 cent coins and the third for 1 and 2 euro coins), or two designs, one for the main unit (euro coins) and one for the subunit (cent coins) (Fornäs, 2007, p. 48 ff.). The number of different designs on coins influences their informational value: minting a different design on each coin in a currency provides the most information on its monetary value, as one could easily determine the value of a coin by looking at its design (Pavlek et al., 2019). The consistent use of numerical marks of value from the 17th century onwards (Kluge, 2016) must have affected how informative designs are about a coin's value. However, most countries today still produce coin series with variable designs. Even though the decision on the number of different designs minted on coins today is mostly arbitrary, our previous findings suggest coin designs do play an important role in the communication of coin value (Pavlek et al., 2019).

The physical properties of the coins, such as the weight, size and colour depend on whether the coin's value is based in the material they are made of (commodity money) or established and regulated by the government (fiat or fiduciary money). Although the properties of the material are not decisive factors of value for contemporary fiduciary coins produced of base metal alloys such as brass, bronze, cupronickel etc., the history of coinage as commodity money based on the value of weighed precious metal has left a mark on physical properties of some contemporary currencies. Some states tend to keep the properties of their coins traditional, reminiscent of the times when the coins were made of two or three different metals (usually gold, silver and bronze). E.g., the US nickel (then called "half dime", 5 USD cents) and dime (10 USD cents) used to be made of silver, and thus were smaller than a penny (1 USD cent), which used to be made of a much cheaper copper. In time, the silver nickels and dimes were replaced by the silvery coloured cupronickel coins, and although the nickels were made larger, the dime size was kept the same (U.S. Department of the Treasury, 2018; see **Figure 1**). Sometimes the sizes of the coins increase with value only within a colour category. For example, the UK copper coloured 2 pence coin is larger than the copper coloured one-penny coin, but the silver 5 pence coin is smaller than the copper coloured 2 pence coin (see **Figure 1**). These discrepancies between size and value could potentially confuse an inexperienced user (Bruce and Hellawell, 1988). The authorities consider possible issues when designing a new coin series, and tend to adapt the coin properties in order to facilitate their use in everyday money exchange, especially for the visually impaired users (European Central Bank, 2018a).

Figure 1: From top to bottom: US dollar coins, UK pound coins, German euro coins, ordered by denomination (value) from smallest to largest.
Source: http://worldcoingallery.com/countries/circ_sets/index.htm

The first coins, produced in Eastern Mediterranean city-states from the end of 7th century BCE, were weighed lumps of precious metal (electrum, silver, gold) marked with designs. Their value was intrinsic, based on the value of the metal corresponding to the silver weight standard (Kraay, 1976; Schaps, 2004; Seaford, 2004). In our previous study on Ancient Greek coins (Pavlek et al., 2019), we predicted that the difficulties with the production of precisely weighed small denominations would create a pressure to clearly distinguish them by encoding more value-relevant information in their designs. However, the results showed that the opposite was true: higher denominations displayed more value-relevant designs.

One possible explanation can be found in the currency denomination structure, i.e., the assortment of denominations and spacing between them. In this respect, ancient systems of currency are similar to the modern ones: the differences in value between the denominations increase in a non-linear manner, i.e., there is a greater difference in value between higher denominations (e.g., 1€ and 2€), than between lower denominations (e.g., 1c and 2c). As the value increases, mistaking one denomination for another becomes increasingly costly. A way to decrease the risk of confusion might be to mark more valuable coin denominations with more distinctive (and therefore more informative) designs.

In this study, we will examine the coin designs and coin sizes in relation to the monetary value denominations in contemporary currencies. We aim to test whether the coin properties become more distinctive as the differences in value between the coin denominations increase.

1.2. Influence of value on the perception of coins

A series of studies used coins to test the influence of value assigned to an object on the perception of its physical properties. The initial study by Bruner and Goodman (1947) found that children of lower socio-economic status overestimated the sizes of coins, but not the sizes of equally large but worthless cardboard discs. The value-size hypothesis has later been revised, suggesting that the relative value of an array of objects produces an accentuation effect on the apparent relative size of the objects (Bruner and Rodrigues, 1953). These findings inspired a number of cross-cultural and cross-modal studies testing the effect of value on perception (Bruner and Postman, 1948; Carter and Schooler, 1949; Eriksen and Hake, 1955; Hitchcock et al., 1976; McCurdy, 1956; Smith et al., 1975; Tajfel, 1959, 1957; Vroom, 1957).

Value emerges as the organizing principle in a set of coins: since coins are used as a medium of exchange, users should be able to infer the value of the coin from its properties. A number of experiments investigated the influence of various coin properties on the user's ability to determine the coin's value. The studies found that people rely on both the coin designs and physical properties such as size, colour, weight and thickness to identify the coin denominations, and have certain expectations on how these properties should correspond to the coin's value. This heuristic is learned through use and applied to new coin series and foreign coinage (Bruce, Gilmore et al., 1983; Bruce and Hellawell, 1988). For instance, when asked to determine the value of unfamiliar British coinage, the Americans tended to expect the coin size to be increasing with the coin's value (Weissman & Furnham, 1985). In a recent study, Horner and Comstock (2005) examined the relative importance of coin designs ("surface details") and the physical features of coins (size, colour, thickness, edge ornaments) for discrimination between the coin denominations. In the absence of coin design, US coins were successfully identified only when all the physical features were known. Although the participants generally did not remember coin designs in detail (usually only the most salient motifs such as the portrait head were remembered), accurate memory did not seem to be necessary for the visual discrimination of coin denominations.

In several studies, subjects expected the differences in size between the coins in a currency series ordered by value to increase with the increasing differences in value between the denominations. McCurdy (1956) analysed the results of early comparison studies and suggested an existence of a “memory schema” in closely ordered series of objects, which allows the correct relative order to be preserved even if there is a tendency to exaggerate the absolute differences in size between coins. He argued that it is “more important to realize that the dime is smaller than the penny than to know either the absolute sizes or the exact amount of difference between them” (McCurdy, 1956, p. 162). Tajfel (1957, 1959) reviewed the previous work on the overestimation of coin properties and concluded that the exaggeration of differences between the stimuli in an ordered series happens only when the variation in size between the stimuli is positively correlated with a variation in value. As the participants were asked to judge the relative differences in size between two coins rather than estimate an absolute difference, they accentuated the differences in order to decrease the risk of confusion. Tajfel’s theory was supported by Smith et al.’s (Smith et al., 1975) experiment on Irish coins. Their experiment showed that when the coin values and sizes are positively correlated, the difference between the coins is overestimated, but not if the sizes and values do not match (i.e., if a coin of a smaller size is more valuable than the bigger coin in a pair). Similar results have been found for the British coins and notes affected by inflation (Furnham, 1983; Lea, 1981). However, a study comparing three Israeli currencies introduced in the period of high inflation (Leiser and Izak, 1987) found no evidence for overestimation of coin size in the series where size was positively correlated with value. They attributed this finding to the fact that in the period of inflation, the public lost their trust in the currency, and the frequent confusing changes of currency led them to stop using the usual rational heuristics of associating the coin size with their value.

1.3. Hypothesis

When considering the coin designs and the coin sizes as important indicators of a coin’s value, it seems that these properties of a coin have to be carefully planned in order to fulfil their purpose. Our previous study showed that the coin designs carried relevant information about the coin’s value (denomination) even in the earliest periods of coin evolution, and that coins of higher value tended to be marked with more informative designs. Based on these results, we suggest that the importance of marking more valuable coins with more salient designs would increase proportionally with the increasing differences in value between the denominations, in order to prevent the rising cost of mistaking one denomination for another. Since the contemporary currency systems have a similar denominational structure as the ancient ones, we would expect that the coin designs of modern currency series would also become more distinctive as differences in value between the coins increase.

The studies on perception of coins suggested that people tend to exaggerate the differences in size between the coins as the differences in value between the adjacent denominations increase (McCurdy, 1956; Tajfel, 1957). The issuers of contemporary currencies create new coin series informed by the results of coin perception studies or public surveys (Bruce, Howarth et al., 1983; Burgoyne et al., 1999; U. S. Government Accountability Office, 2002). If the coin properties are designed in a way to accurately reflect the denominational structure of a currency (coin values), we would expect the differences in size between the coin denominations to increase with the differences in value.

We will assess the differences between the coins in a pairwise comparison of the adjacent coin denominations inside each currency. The order of coin denominations in a currency is determined by their value: in a currency with the denominations A, B, C, D, E, where A is the lowest and E is the highest, the adjacent denominations A and B are closest in value.

The differences in value between the denominations in a currency increase non-linearly: the value gap between A and B is smaller than the one between D and E. As differences in value between coin denominations increase, the differences between coins in terms of their designs and sizes should become increasingly salient in order to minimize the increasing risk of confusion. We expect that the probability that adjacent coin designs differ would increase as differences in value between the coin denominations in a currency grow. Based on the result of our previous study, we expect this increase to be non-linear: the probability for the designs to differ should be greater for higher denominations. Although it is possible that the relationship between the increasing distinctiveness of adjacent coin designs and coin value differentials could be linear, it is hard to envision a linear relationship between the differences in sizes and differences in values, as it would result in impractically large coins, which would be extremely inefficient and expensive to produce. Therefore, we expect this relationship to be non-linear.

1.4. Dataset

We have obtained the list of modern currencies in circulation from the web page of the ISO 4217 International Standard for currency codes (International Organization for Standardization, 2015). Because we are interested in currencies using physical tokens (coins), we disregarded the international units of account, bond market units and metal standards, which also have their own ISO codes. We removed "European Union" from the list of state entities, and collected the data on national issues of euro coins of Eurozone member states. This left us the list of 157 currencies issued and used by 253 state entities.

The data on the coin denominations of these currencies was collected from (in order of priority) the respective central bank websites (see App. 3), the Standard Catalogue of World Coins (Cuhaj, 2015), and online sources (Wikipedia, Numista forum; see App. 3). We looked for the most recent circulating standard coin series, and collected the information on the issuing state (e.g., Germany), the name of the currency (e.g., euro), and the coin denominations (e.g., 1 cent, 2 cent, 5 cent…). For each coin denomination in a currency, we noted the size (diameter in mm), metal, colour, and the obverse and reverse design descriptions. As we found that there are no Lao kip (currency of Laos) coins in circulation, we excluded this currency from the list. After the data collection phase, the database consisted of 1604 coin denominations.

1.4.1. Data exclusion criteria

At this point, we had to exclude some data points in order to deal with several possible issues arising from the various types of currencies used in the world today.

Some currencies are used by multiple countries, but there are differences in the way the coins of these international currencies are produced. For example, the euro coins are minted by each of the Eurozone countries, and feature unique national designs in addition to the common European designs (European Central Bank, 2018b). In such cases, we considered each national series as a separate currency (e.g., German euro, Belgian euro). We disregarded the countries which use the euro as their only currency, but are not members of the European Union and therefore do not produce the local variants of euro coin designs (Åland Islands, Montenegro, French dependent territories, in total 88 data points). In case of common currencies whose designs do not vary, i.e., the members of the monetary union do not produce special coin series, we counted only one presence of the currency, and disregarded all the rest (in total 139 data points). E.g., West African Franc (CFA Franc BCEAO) is used by eight different countries, but the coin designs do not change by the country as is the case with the Euro coins.

On the other hand, some currencies are centrally produced, but are used by multiple countries either as the sole official currency or in addition to the local currency. The best example is the US dollar, which is officially used not only in the US and their territories, but also in 7 other countries and 3 non-US territories (Adkins, 2015). We only considered such internationally used currencies once, when they were listed with the issuing state (in the US dollar example, the US). We excluded all the other uses of the foreign currencies by other states or entities (in total 229 data points).

If the denominations of a currency are produced with variable designs (e.g., two or more parallel series), we kept only the most frequent variant, and excluded the commemorative design variants (19 data points in total).

After exclusions, we checked the dataset again to identify possible mistakes. We added four data points we previously missed, and excluded one that has been discontinued. Our final dataset has 1132 data points - coin denominations belonging to 182 currencies (see App. 1). From this dataset, we will create the pairwise comparison dataset, which will be used in hypothesis testing (see section 1.5.1).

1.4.2. Sources

Our dataset was informed by 314 different sources in total. We noted the sources used for each data point, and, in cases where we used multiple sources, whether they provided the same information. The majority of the data was obtained from the central bank websites (36%), and the Standard Catalogue (26%), followed by Wikipedia (25%) and Numista (13%). The agreement between the sources was strong: in 95% of cases, the sources used for one data point agreed 100%, and the agreement was never smaller than 50% (computed over the final dataset N = 1132).

1.5. Methods

1.5.1. Pairwise comparison dataset

In order to test our hypothesis, we will first measure the differences in value, size and design between adjacent coins in a pairwise comparison. For example, if a currency has five coin denominations A, B, C, D, E ordered by value (so that A<B<C<D<E), we will compare the values, sizes and designs of the adjacent pairs [A, B], [B, C], [C, D] and [D, E].

The difference in value between the coins in a pair will be computed as a relative difference, using the smallest denomination in a currency as a baseline. To illustrate, in euro currencies the smallest value is 1 cent. Therefore, the difference between 1 euro cent and 2 euro cent is 1, but between 1 and 2 euro is 100. However, there are currencies troubled by inflation, whose coins are produced only in large denominations, as the small coins have been withdrawn from circulation. For example, Iranian rial's smallest coin has the value of 50 rial, and the largest of 5000 rial. In this example, our baseline for computing the difference in value is 50, so the difference between 50 and 100 rial is 1, between 100 and 250 rial 3, etc.

The difference in size will be measured as a difference in *mm* between the diameters of the coins in a pair. The coins typically come in several different colours mimicking the precious metals ("golden" coins, "silver" coins, "copper" coins). The difference in colour between adjacent coins in a pair will be coded as a binary variable (1 = colours differ, 0 = colours are the same).

The difference in design will be coded as a binary variable with value 1 if the designs of two coins in a pair differ, and 0 if the coins in a pair have identical designs. Two coders will independently determine the difference in coin designs. The coders will be provided with an Excel document containing two sheets: the guidelines, and the coding sheet with the obverse and reverse design descriptions of coin 1 and coin 2, and the coding column (see example, App. 2). We are using the standardized descriptions provided by the sources instead of images to minimize the possibility of confusion due to the image size and detail level (most images available are very small and often of low quality). Both coders will compare the designs of all the pairs in the dataset. We will then test the agreement between the coders with the inter-rater reliability test in R using Cohen's Kappa for categorical data (Cohen, 1960). In order to proceed, we require the agreement to have a Kappa of at least .51 (Hallgren, 2012).

The summary of the key variables is given in **Table 1**. These variables will be used to create models and test the hypothesis. An example of the pairwise dataset for small German euro cents is given in **Table 2**.

variable	type of variable	unit of measurement
DIFF.VALUE	continuous	smallest value in a currency
DIFF.DESIGNS	binary	0 = same design; 1 = different design
DIFF.SIZE	continuous	diameter (mm)
DIFF.COLOUR	binary	0 = same colour; 1 = different colour

Table 1: Summary of the key variables used in the models.

CURRENCY	PAIR	DIFF.VALUE	DIFF.SIZE	DIFF.DESIGN	COLOUR
Germany.Euro	1.cent_2.cent	1	2.5	same (0)	same (0)
Germany.Euro	2.cent_5.cent	3	2.5	same (0)	same (0)

Table 2: Example of the pairwise dataset.

1.5.2. Testing the relationship between the differences in value and differences in coin designs

Because the differences in designs are coded as a binary variable, we will model the relationship between the differences in value (continuous variable) and the probability that the coin designs differ as a logistic mixed effects model, using the *lme4* package in R (Bates et al., 2015).

We will build three models:

1. a null model to account for the possibility that the increasing differences in value do not affect the differences in coin designs

2. a model testing the possibility for a linear relationship between the differences in value and differences in coin designs, and

3. a model assuming the predicted non-linear relationship between the differences in value and differences in coin designs.

In all three models, we will control for the random effect of currency in order to account for the structural differences between multiple currencies our coin denomination pairs belong to[7]. The summary is given in **Table 3.**

relationship type	model formula	dependent variable	random intercept	independent variable
null	DIFF.DESIGNS ~ (1|CURRENCY)	DIFF.DESIGNS	CURRENCY	none
linear	DIFF.DESIGNS ~ (1|CURRENCY) + DIFF.VALUE	DIFF.DESIGNS	CURRENCY	DIFF.VALUE
non-linear	DIFF.DESIGNS ~ (1|CURRENCY) + log (DIFF.VALUE)	DIFF.DESIGNS	CURRENCY	DIFF.VALUE (log-transformed)

Table 3: Summary of the models predicting the differences in designs.

The hypothesis will be tested by comparing the Akaike information criterion (AIC) of all three models. We expect the predictor (DIFF.VALUE) to have a positive estimate, and the model predicting a non-linear relationship to have the best fit, indicated by the lowest AIC score.

1.5.3. Testing the relationship between the differences in value and differences in coin size

Since both the difference in sizes and values of coins are continuous variables, it allows us to model the relationship between them with linear mixed effects models, using the *lme4* package in R (Bates et al., 2015). We will again control for the random effect of currency.

In some currencies, the coin sizes vary inside each colour category, with the sizes decreasing at the colour boundaries. In these cases, the difference in size between the coins in a pair would be negative. In order to control for this issue, we will include a random slope for difference in colour in addition to the binary independent variable. Here we will build only two models:

[7] There is a possibility that the currencies of monetary unions (we will call them “super-currencies”) such as euro will influence the distinctiveness of coins in important ways. If we find this to be the case, the data will be nested by super-currencies. E.g. the German euro, Italian euro, French euro etc. will be considered together as a single euro super-currency. Most currencies in our dataset do not belong to a super-currency, so they will be assigned to a super-currency category identical to themselves (e.g. US dollar, Swiss franc, etc.).

1. a null model to account for the possibility that the increasing differences in value do not affect the differences in coin sizes, and

2. a model assuming the predicted non-linear relationship between the differences in value and differences in coin sizes.

We do not believe the difference in coin sizes should increase linearly in relation to the differences in value. **Table 4** summarizes the models.

relationship type	model formula	dependent variable	random intercept	independent variable
null	DIFF.SIZE ~ (1+DIFF.COLOUR|CURRENCY) + DIFF.COLOUR	DIFF.SIZE	CURRENCY + random slope for DIFF.COLOUR	DIFF.COLOUR
non-linear	DIFF.SIZE ~ (1+DIFF.COLOUR|CURRENCY) + DIFF.COLOUR + log (DIFF.VALUE)	DIFF.SIZE	CURRENCY + random slope for DIFF.COLOUR	DIFF.COLOUR DIFF.VALUE (log-transformed)

Table 4: Summary of the models predicting the differences in size.

Again, we will test our hypothesis by comparing the AIC scores of the two models. We expect a positive estimate for the predictor (DIFF.VALUE), and that the model predicting a non-linear relationship will have a lower AIC score.

Appendices

App.1: contemporary currencies dataset:
currencies_dataset.csv (+ readme_dataset.txt)

App.2: coding sheet for differences in designs (example):
coding_sheet.xlsx (+ readme_codingsheet.txt)

App.3: list of online sources used for the dataset:
online_sources.pdf

All appendices can be accessed in the *Preregistration* folder of the OSF repository.

2. Results report

2.1. Introduction

This report summarizes the results of the study testing two hypotheses on the relationship between the increasing differences in value between the coin denominations in a currency, and the differences between the coins in terms of their sizes and designs. The study was preregistered on 25 January 2019. The data and code are provided in the OSF data storage.

The dataset of 1132 coin denominations belonging to 182 different contemporary currencies (see currencies_dataset.csv in the OSF data storage, folder *PairwiseSetup*) was used to create a pairwise comparison dataset, following the preregistered methods (see above, section 1.5.1). The code and data can be found in the OSF data storage (folder *PairwiseSetup*). First, we determined the face value of each coin denomination in each currency in relation to the subunit of a currency. E.g., for euro currency, euro is the main unit and cent is the subunit, valued 1/100 of a euro. Therefore, the face value of a 1-cent coin is one, and the face value of a 1-euro coin is 100. We used these face values to arrange the coin denominations inside each currency in an ascending order, and then we coupled the adjacent coin denominations in 950 pairs. Next, we computed the difference in size (diameter in *mm*) and difference in colour (1 = different, 0 = same) between the coins in each pair. In order to compute the differences in value, we first calibrated the face values (described above) so that the values of the coin denominations are measured in relation to the smallest value in the currency they belong to ("Smallest Coin"). E.g., the smallest value in the euro currency is 1 cent, so the difference between 10 and 20 cent is 10, expressed in 1-cent units. The smallest face value in Algerian dinar currency is ¼ dinar, so the difference between 10 and 20 dinar is 40, expressed in quarter-dinar units. This has been done in order to avoid having the differences in value expressed in very large numbers (see above, section 1.5.1).

Two independent coders coded the differences in design between the coins. The coders were blind to our predictions; however, they were familiar with the general idea of the study and the data, as they were involved in data collection. The coders were presented with the coding sheets including the dataset of 950 coin pairs (see example coding_sheet.xlsx in the OSF data storage, folder *Preregistration*). The coders' task was to compare the obverse and reverse design descriptions of two coins in a pair, and code the difference in design as 1, if the coins in a pair have different designs and 0, if both coins have an identical design (considering both sides of each coin). We ran an inter-rater reliability test (Cohen's unweighted Kappa for 2 coders) using *irr* package in R (Gamer et al., 2019). The code is available in the OSF folder *DoubleCoding*. The test has shown a significant agreement between the coders (Kappa = 0.983, N subjects = 950), so we could proceed with our analysis. The coin pairs coders disagreed upon (N = 7) were removed from the dataset – the finished pairwise dataset consists of 943 coin pairs (see currencies_pairs_full.csv in folder *DoubleCoding*).

2.2. Results

We tested two preregistered predictions: for coin denominations of a currency ordered by value, (1) the probability that the coin designs of the adjacent coin denominations differ would increase with the value differentials, and (2) the differences in sizes between the adjacent denominations would increase in a non-linear manner with the increasing differences in value. We built five models: three modelling the relationship between coin design differentials and value differentials, and two modelling the relationship between coin size differentials and value differentials. We tested our predictions by comparing the model's Akaike information criterion (AIC) scores. While preforming the preregistered analyses, we noticed some patterns in our data that might have influenced our results. These issues were addressed in re-analyses by introducing additional exclusion criteria. All models were built using the *lme4* package in R (Bates et al., 2015). The code is available in the OSF data storage (*Analysis* folder).

2.2.1. Testing the relationship between the differences in value and differences in coin designs

a. Preregistered analysis

The results are summarised in **Table 5** below.

model	model formula	AIC	random effect	fixed effects	N
null	DIFF.DESIGNS ~ (1|CURRENCY)	861.5	CURRENCY variance = 13.04 std .dev. = 3.61	Intercept β = 2.47 st. err. = 0.49 z-value = 4.997 p < 0.0001	coin pairs: 943 currencies: 182
simple	DIFF.DESIGNS ~ (1|CURRENCY) + DIFF.VALUE	851.0	CURRENCY variance = 14.18 std .dev. = 3.76	DIFF.VALUE β = 0.006 st. err. = 0.002 z-value = 3.162 p = 0.0016	coin pairs: 943 currencies: 182
log-transformed	DIFF.DESIGNS ~ (1|CURRENCY) + log (DIFF.VALUE)	840.3	CURRENCY variance = 15.56 std .dev. = 3.94	log DIFF.VALUE β = 0.37 st. err. = 0.08 z-value = 4.587 p < 0.0001	coin pairs: 943 currencies: 182

Table 5: Results summary: predicting the differences in designs

A significantly positive estimate for the effect of DIFF.VALUE suggests that the designs of the neighbouring coins in a currency differ with an increasing probability, as the value differentials increase. The effect is more significant when the predictor is log transformed, and the model assuming a non-linear relationship fits the data better than the other two models, indicated by the lowest AIC score (see **Table 5** above).

b. Re-analysis with additional exclusion criteria

We ran an additional analysis after excluding currencies whose designs always differ between coin denominations (99), and the ones whose coin designs are always the same (19), resulting in a dataset of 386 coin pairs belonging to 64 currencies. The analysis followed the preregistered plan, testing the predictions by comparing three logistic mixed effects models constructed using *lme4* package in R. The original finding was confirmed (see **Figure 2**). The model predicting the non-linear relationship between differences in designs and differences in values again had the lowest AIC score ($AIC_{null} = 521.4 > AIC_{simple} = 513.8 > AIC_{log\text{-}transf.} = 504.3$), and the log-transformed predictor had a significant positive estimate ($\beta = 0.308$, st. err. = 0.07, z= 4.16, $p < 0.0001$).

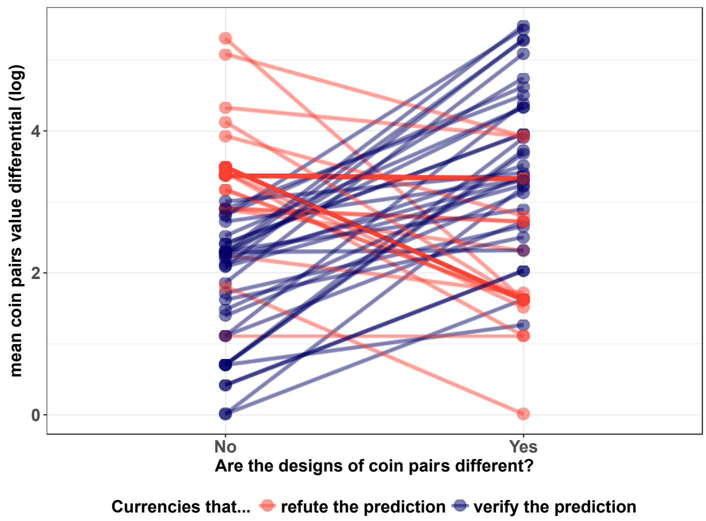

Figure 2: In pairs of coins with higher value differentials, coins are marked with distinct designs. Each line stands for one currency (total n = 64), and shows the average value differential between adjacent pairs of coins (e.g., one euro-two euros), depending on whether or not the two coins share the same design (left) or have different designs (right). The majority of currencies verify our prediction (in blue): pairs bearing distinct designs tend to show higher value differentials. Value differentials are given in Smallest Coins, i.e., as multiples of the value of the smallest coin within each currency.

2.2.2. Testing the relationship between the differences in value and differences in coin size

a. Preregistered analysis

The results are summarised in **Table 6** below.

model	model formula	AIC	random effect	fixed effects	N
null	DIFF.SIZE ~ (1+DIFF.COLOUR|CURRENCY) + DIFF.COLOUR	4467.6	CURRENCY variance = 0.11 std .dev. = 0.33 rand. slope variance = 1.93 std .dev.= 1.39	Intercept β = 2.44 st. err. = 0.11 t-value = 22.37 DIFF.COLOUR β = -2.20 st. err. = 0.19 t-value = -11.11	coin pairs: 943 currencies: 182
log-transformed	DIFF.SIZE ~ (1+DIFF.COLOUR|CURRENCY) + DIFF.COLOUR + log (DIFF.VALUE)	4468.1	CURRENCY variance = 0.11 std .dev.= 0.33 rand. slope variance = 2.00 std .dev. = 1.42	Intercept β = 2.30 st. err. = 0.15 t-value = 14.84 DIFF.COLOUR β = -2.24 st. err. = 0.20 t-value = -11.13 log DIFF.VALUE β = 0.07 st. err. = 0.05 t-value = 1.25	coin pairs: 943 currencies: 182

Table 6: Results summary: predicting the differences in size

The log transformed predictor DIFF.VALUE had a positive estimate, but the AIC score of the model including the predictor was higher than the AIC score of the null model (see **Table 6**), suggesting that the predictor did not improve the model fit. The fixed effect for DIFF.COLOUR had a strongly negative estimate, which means that the difference in size is on average smaller when two coins in a pair differ in colour (see **Figure 3**).

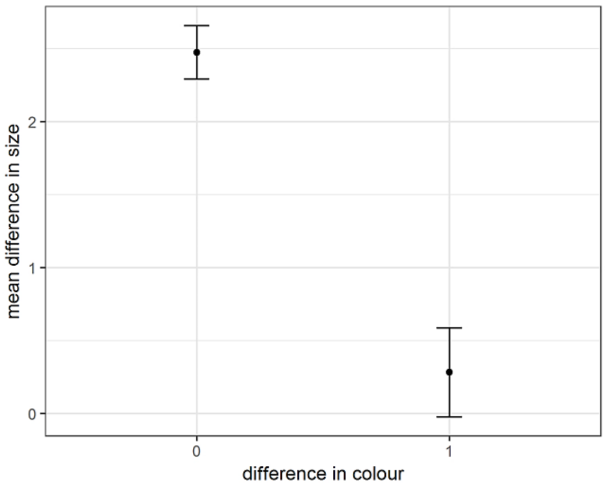

Figure 3: Mean difference in size (point) for coin pairs with same colour (DIFF.COLOUR = 0) and coin pairs whose colours differ (DIFF.COLOUR = 1). Error bars indicate 95% confidence intervals.

b. Re-analysis with additional exclusion criteria

We re-ran the original analysis after merging the currencies whose coins do not differ in physical characteristics (size and colour), only in coin designs. Two such examples are the euro currencies (N= 23), and two Pacific franc variants (French Polynesian and New Caledonian CFP franc). These families of currencies show no internal variation in coin sizes, while exhibiting clear internal variation for designs. When testing the differences in designs, it made sense to treat these currencies separately (according to the preregistered plan, see above, section 1.4.1), but in case of the size differentials it is unnecessary. We combined 23-euro coins in a single "euro" currency and two Polynesian francs in a single "CFP.franc" currency. This gave us a dataset of 783 coin pairs belonging to 159 currencies. This time we ran three models, a null one, a simple one including a non-transformed predictor (DIFF.VALUE) and a model including a log-transformed predictor. The results of this repeated analysis were similar to the original results. Including a predictor resulted in a slightly increased AIC score ($AIC_{null} = 3811.5 < AIC_{simple} = 3812.9$), which means the model was not improved. The estimate for DIFF.COLOUR was again negative (for the simple model $\beta = -2.15$, st. err. = 0.23, t-value = -9.17). We also found a clearly positive intercept

(2.47, SE = 0.13, t = 19.2), indicating that the higher-value coin of the pair is on average larger than the lower-value coin (by around 2.5 millimetres). Log-transforming the predictor did not change the results ($AIC_{log\text{-}transf.}$ = 3813.3), nor did excluding four outlier pairs with high value or size differentials.

For the second reanalysis, we took the reduced dataset of 783 coin pairs described above, and extracted the subset of coin pairs which do not differ in colour (N = 457, 142 currencies), in order to control for the possible effect of individual coin colours on the differences in coin sizes. The models included only a random effect for currency, without the random slope or fixed effect for colour. The results of this reanalysis are similar to the main result: the predictor (log DIFF.VALUE) failed to improve the model ($AIC_{null} = 2078.7 < AIC_{simple} = 2079.6 < AIC_{log\text{-}transf.} = 2080.6$).

2.2.3. Post-hoc analysis: coin sizes and values

The results of the preregistered analysis suggested that the differences in value between the coins in a currency are better reflected by the differences in their designs – differences in coin sizes do not seem to be a reliable source of information about the value differentials. However, it does not mean that the coin sizes do not indicate coin values.

In order to verify this, we ran three linear mixed effects models on the dataset of single coins (currencies_dataset.csv) instead of coin denomination pairs. The null model included a random effect for currency a coin belongs to and the random effect for a coin's colour, while the second model included a fixed effect for coin value in relation to the smallest denomination in a currency. The third model was equivalent to the second one, except the coin value was log-transformed. The data and code are available in the OSF data storage (currency_models.R, *Analysis* folder). We again merged the euro and CFP franc currencies together, which gave us the dataset of 949 coin denominations, belonging to 159 currencies. The model with a log-transformed fixed effect for value outperformed the other two ($AIC_{null} = 5134.40 > AIC_{simple} = 5119.85 > AIC_{log\text{-}transf.} = 4578.14$). The results show a significant positive effect of coin value (log transformed) on the coin size ($\beta = 1.59$, st. err. = 0.046, t-value = 34.16), which confirms a strong non-linear relationship between the coin sizes and coin values. Excluding 16 outliers (coins with values above 1000) did not change the result (see **Figure 4**).

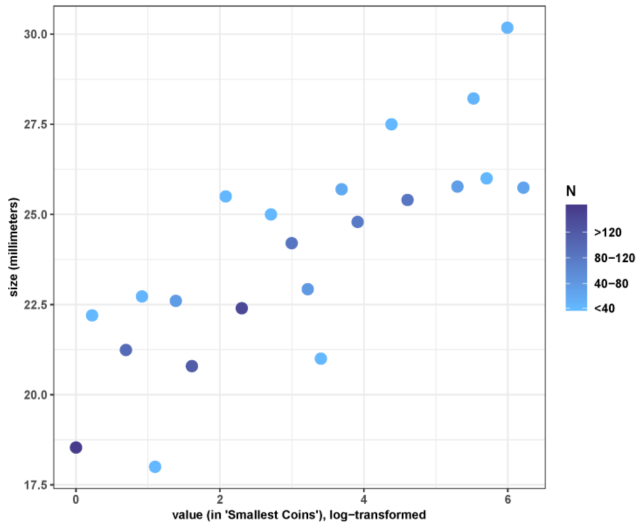

Figure 4: The size of coins reflects their value on a logarithmic scale. Each data point is one set of coins sharing the same value (with number of coins indicated by dot colour). Total n: 933 coins from 159 currencies, excluding 16 outlier coins.

2.3. Summary

We have tested two predictions about the ways coin properties (designs and sizes) reflect differences in value between the coin denominations of a currency. Our prediction that the coin designs of two adjacent coins in a currency ordered by value are increasingly likely to differ as the differences in value between them increase has been confirmed. Our second prediction, assuming that the differences in coin sizes increase with the differences in value has not been confirmed. However, an additional analysis confirmed that the absolute increase in coin values is indicated by a non-linear increase in coin sizes.

3. Additional analyses registration

This document outlines the additional measures and analyses suggested by two reviewers after the initial submission of the paper reporting this study, initially preregistered on 25th of January 2019. We will revise our measures of coin design difference and use a different method to express the value of each coin. The rationale and methods for each analysis are described in detail. For ease of reference, the original preregistration and report are appended to this document.

3.1. Additional measures

3.1.1. Designs similarity

In our original study (see section 1.5.1), we arranged the coin denominations of the world's currencies into pairs of adjacent value (e.g., for euros, 1-2 cents, 2-5 cents…1-2 euros), and tested whether the pairs with larger value differentials are more likely to carry different designs – images on both sides of a coin. In order to assess this difference, we asked two coders to determine whether the two coins in each pair have the same design (0) or their designs differ (1). However, this way of coding the similarities/differences in coin designs might not capture the degree of similarity between the coins, which could lead to users being more likely to confuse some coins than others.

We will attempt to create a new measure of difference in designs, based on a similarity scale. Two independent coders will assess the difference between the coins in each pair of our pairwise dataset (currencies_pairs_full.csv), and mark their answer on the six-point Likert scale. In order to keep this new measure as similar as possible to the original binary coding, on our scale "0" will signify that two coins have identical design, and "5" that their designs completely differ. The example of the coding sheet is presented in **Table 7**.

This time the coders will compare photographs of the coins instead of design descriptions. The photographs of both sides of each coin will be downloaded from the Numista forum website (Numista Team, 2007). The coders will be presented with images of pairs of coins displayed side by side on the computer screen. All images will be presented in grayscale, equal in size, and their contrast will be adjusted accordingly to make the design features visible (see example, **Figure 5**). The coders will be instructed to focus on the graphic design only, and disregard the numerical value marks and inscriptions. The order of the coin pairs will be randomised, in order to avoid the judgment being influenced by the other pairs belonging to the same currency.

<table>
<tr><td colspan="4">Rate the similarity between two coins. Compare both sides of each coin. Focus on the graphic design (images), and disregard the inscriptions (text) and nominal value (number or text).
How similar are COIN1 and COIN2? Write the number in the COMPARE column.
0 = completely identical
1 = similar
2 = slightly similar
3 = slightly different
4 = different
5 = completely different</td></tr>
<tr><td>CURRENCY</td><td>COIN1</td><td>COIN2</td><td>COMPARE</td></tr>
<tr><td>Mexican.Peso</td><td>20.centavo</td><td>50.centavo</td><td></td></tr>
</table>

Table 7: Example of coding sheet: similarity of coin design.

Figure 5: Example of photography comparison stimulus.

We will test the agreement between the coders by an inter-rater reliability test in R (package *irr*, Gamer et al., 2019), using Cohen's Kappa for categorical data. Since this variable is ordinal, we will use a weighted Kappa (Cohen, 1968). We require the agreement to have a Kappa of 0.80 (indicating almost perfect agreement) in order to proceed to use this difference gradient to test the prediction described in section 3.3.1.a. (Algren, 2012).

3.2. Value standardization

Our study was testing how different coin properties reflect the value differentials between the coin denominations in a currency. The value of each coin was expressed in relation to the smallest coin denomination in that currency (e.g., for euros, 1 cent coin), in order to account for the differences in the number and values of coin denominations produced for the world's currencies (see section 1.5.1). Although this method of value standardisation works well for the purposes of testing the predictions focusing on the relative differences between the coins of the same currency, we were encouraged to test the robustness of our results using another standardisation method, which would express the value of each coin in absolute terms, in relation to coins of other currencies.

A good method for comparing the value of different currencies is using the Purchasing Power Parity (PPP), a metric based on the basket of goods, generated by the International Comparison Program (ICP) ("International Comparison Program (ICP)," n.d.). Although the PPPs are calculated for almost all of the world's countries (e.g., 199 countries participated in 2011, cf. "ICP 2011," n.d.), the fact that they are calculated by country, and not by currency presents a major disadvantage to adopting them as a global standard of value in our analyses.

Another way to compare the values of coins across currencies is by converting all values to a single currency, e.g., the US dollar. The fixed daily exchange rates for the US dollar can be obtained from the UN Treasury website ("UN Operational Rates of Exchange," 2019) for all currencies except for the Taiwanese new dollar, which can be found on the Central Bank website ("NT$/US$ Closing Rate," 2019). Some currencies are pegged with another currency at par, meaning their value is equivalent. In our dataset, there are 12 such currencies. the Cook Islands dollar, pegged with New Zealand Dollar; Cuban peso (and convertible peso), Bahamian dollar, Bermudan dollar, Panamanian Balboa and Zimbabwe bond coins, pegged with the US dollar; and pound variations in British dependent territories (Falkland Islands, Gibraltar, Guernsey, Isle of Man and Jersey), pegged with the British pound. The corresponding conversion rates will be applied to these currencies.

We decided to use the coin value expressed in dollars (VALUE.USD) as a global standard in a repeated test of our predictions (see section 3.3.1). We will use the conversion rates to express the nominal value of each coin in corresponding amount of US dollars. The base for the conversion will be each coin's value relative to the main currency unit instead of the smallest coined denomination. For example, the value of 1 euro cent will be counted as 0.01 euros, and the value of 50 cent as 0.5 euros.

The datasets including the converted values (currencies_dataset_additional.csv, currencies_pairs_additional.csv) can be found in the OSF data storage (*Additional Analyses Registration*).

3.3. Additional analyses

3.3.1. Repeated preregistered analyses with values standardized across currencies

We will repeat our main analyses testing the relationship between the value differentials and differences in coin designs (prediction 1) and differences in size (prediction 2) for pairs of coins, as well as the post-hoc test which is looking at the sizes and values of single coins (see section 2.2.3). Instead of the values based on the "Smallest Coin", we will use the "global value" of each coin, standardized in US dollars (VALUE.USD; see section 3.2 above). The preregistered models will otherwise remain unchanged.

Converting the face values of coin denominations to a different currency will transform the difference in value computed between two coins of a value-adjacent pair, depending on the exchange rate between each currency in relation to the US dollar. For example, the value differential between 1 and 2 euros, expressed in the relation to the smallest coin denomination in the currency (1 cent), is 100. If we convert the face values of these coins into US dollars (1 EUR = c. 0.91 USD; 2 EUR = c. 2.20 USD)[8], this difference will equal 1.29. However, the relative difference in value between two coins of the same currency will remain the same.

Using the revised measure will likely increase the importance of the variance between the currencies on both dependent measures (value differentials between coins and absolute values of individual coins). Our models control for this variance by including the random effect for currency. We therefore do not expect to see any difference to the original results for the estimates of the fixed effects of value differentials and raw values.

The view that coin sizes are linked to the actual economic value of coins, as opposed to their face value, is not without proponents (e.g., Brysbaert and D'Ydewalle, 1989) but is rather marginal. We do not attempt to test this claim. Introducing a globally standardised measure of value based on the current exchange rates is intended only as a robustness test of our original results. We still believe the "Smallest Coin" measure is the most appropriate measure for the effect we want to test

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[8] United Nations Treasury. (2019, 13.09). UN Operational Rates of Exchange. Retrieved September 24, 2019, from https://treasury.un.org/operationalrates/OperationalRates.php

a. Prediction 1: The difference in coin designs

The original analysis confirmed our first prediction, expecting the designs of two coins in a pair of adjacent denominations to be more likely to differ as the value differentials between the coins increase (see section 2.2.1). We again expect to see this trend, indicated by a positive estimate for the predictor (value differentials). The previous analysis also found this relationship to be non-linear, best predicted by the log-transformed value differentials. We again expect the model including a log-transformed predictor to have the lowest AIC score.

In this repeated analysis, we will use the same parameters and models as in the original analysis (see sections 1.5.1 and 1.5.2), with the exception of the main predictor, difference in value. The value differentials expressed in "Smallest Coin" will be replaced by the differentials computed with coin values converted to US dollars (DIFF.VALUE.USD; see currencies_pairs_additional.csv). We will run the analysis excluding the currencies with same designs on all denominations (n=19) and the ones with a different design on each denomination (n=99). In the original analysis, the result has not changed after this exclusion.

b. Prediction 2: The difference in coin sizes and the relationship between size and value

Our prediction assuming the difference in size between the coins in an adjacent pair of denominations increases with the value differentials was not confirmed (see section 2.2.2). However, a positive intercept indicated that in a pair of coins, the higher value coin tends to be larger than the lower value one. A repeated test with absolute sizes and values of individual coins found that coin sizes do correspond to their values, with sizes indicating the log-transformed values better than the raw values.

We will repeat both analyses, the one focusing on coin pairs and their relative differences in value and size (using currencies_pairs_additional.csv), and the other looking at sizes and values of single coins (using currencies_dataset_additional.csv). For the first analysis (with coin pairs), we will follow the preregistered methods (see section 1.5.3), but use the value differentials based on the exchange values (DIFF.VALUE.USD). The test with absolute coin sizes and values will be performed by comparing three models: a null model with the (raw) coin size as a dependent variable, and two random intercepts (for currency and colour), a model including the predictor (the coin values), and the model including the log-transformed predictor (see section 2.2.3). Instead of the values based on the "Smallest Coin", will use the values expressed in US dollars. We do not expect the results to differ from our original finding.

After the initial analyses, we will test the robustness of our results by removing the pairs with excessive size and value differentials, and by removing the coin pairs that differ in colour. These exclusions did not affect the results of the original analysis (see section 2.2.2.a and 2.2.2.b).

3.3.2. Repeated preregistered analysis with designs similarity measure

Using the new measure of designs similarity (see section 3.1.1), we will repeat the analysis testing how well the differences in designs on adjacent coin denominations match the value differentials (see sections 1.5.1 and 1.5.2). We will keep all other parameters the same. We expect to see less similarity in the coin designs with the increasing value differentials. This relationship should be best explained by the log-transformed value differentials.

3.4. Additional predictions

3.4.1. Testing the relationship between the differences in value and differences in colour

In the original study, we focused on two coin properties, design and size. While testing the relationship between coin sizes and values, we controlled for the fact that the coin sizes tend to increase inside a colour category (Bruce, 1989; Bruce and Hellawell, 1988). For example, the sizes of small copper-coloured 1, 2 and 5 euro cents increase with value, but the first coin in the golden-coloured tier, 10c, is smaller in size than the copper-coloured 5c. We found a strongly negative estimate for the effect of difference in colour, suggesting that the difference in size between the coins of an adjacent pair of denominations is less important when the colour change indicates the change in value (see section 2.2.2).

The colour of the coins comes from the alloys used as coinage metals. The choice of alloys is based on various factors, such as their availability and the properties suitable for the requirements of production and use of coins in circulation (Euro Banknotes and Coins: Technical Features, 1995). However, the colour of modern coins is primarily a design feature, since the face value of the circulation coins no longer corresponds to the market value of their metal content. If the changes in colour reflect the changes in coin value, we could expect this relationship to be similar to what we have observed in the case of coin designs.

We will test whether the two coins in a pair of adjacent denominations are more likely to differ in colour if their value differentials are bigger, by adopting the methods used for testing the relationship between the differences in coin designs and values. We will build three logistic mixed effects models (see **Table 8**): a null model including the difference in colour (DIFF.COLOUR) as the dependent variable, and the random effect for currency; a model also including value differentials (DIFF.VALUE) as a predictor; and the model with the log-transformed predictor (logDIFF.VALUE).

relationship type	model formula	dependent variable	random intercept	independent variable
null	DIFF.COLOUR ~ (1|CURRENCY)	DIFF.COLOUR	CURRENCY	none
linear	DIFF.COLOUR ~ (1|CURRENCY) + DIFF.VALUE	DIFF.COLOUR	CURRENCY	DIFF.VALUE
non-linear	DIFF.COLOUR ~ (1|CURRENCY) + log (DIFF.VALUE)	DIFF.COLOUR	CURRENCY	DIFF.VALUE (log transformed)

Table 8: Summary of the models predicting the differences in colour.

We will compare the Akaike information criterion (AIC) of all three models, and expect the model with log-transformed predictor to have the lowest AIC score, indicating that it outperforms the other two. We also expect the predictor to have a positive estimate.

This analysis will be performed twice, once with each of our standardised value differentials: the one expressed in "smallest coins" (DIFF.VALUE; see section 1.5.1), and the other, standardised in US dollars (DIFF.VALUE.USD; see section 3.2).

3.4.2. Testing the joined effect of the different coin properties on coin value

In our study, we look at coins as a system of tokens of exchange providing to users the information on the monetary value they represent. This information is encoded in the physical properties and graphic designs on coins. Our general hypothesis assumed that, in order to be efficiently informative about their value, the coin denominations of a currency should be more distinct as the value differentials between them increase. We have initially focused on designs and sizes separately. Whereas the options for the choice of designs are virtually unlimited (except for the technical and spatial requirements), the sizes are often strictly regulated to combat counterfeiting, and to keep the coins user-friendly and profitable. The colour of the coins is a different case, because although the technical properties of the material and the security features are the main factors in the choice of the coinage alloy, this choice also has an aesthetic component, which makes the colours a property similar to the graphic design.

Another reason why we have not looked at the possible interactions between the various properties has to do with their structure: unlike designs and colours, which are categorical, sizes are continuous quantities, similar to the coin values. While in the case of designs and colours we can only assess the likelihood of them being distributed over coin denominations in a way that reflects the increasing value differentials (higher denominations being more likely to bear distinct designs and be of distinct colour), the sizes can more closely correspond to values.

However, to investigate the possible correlations between sizes and colours (sizes increasing inside a colour category), as well as designs and colours (in some currencies, the design changes with the colour category), we will run an analysis taking in account the possible interactions between the coin properties.

We will compare two models, one with raw value differentials, and another with log-transformed value differentials as dependent variables. Both models will include the random effect for currency, three predictors (DIFF.DESIGN, DIFF.SIZE, DIFF.COLOUR) and two interactions (between DIFF.DESIGN and DIFF.COLOUR and between DIFF.SIZE and DIFF. COLOUR). We will run both models with originally coded value differentials (based on “Smallest Coin”, DIFF.VALUE), and the standardised one (DIFF.VALUE.USD). We will also use both the original coding of differences in design, and the revised coding (see section 3.1.1).

4. Additional analyses report

This report summarises the results of additional analyses requested by two reviewers. Additional analyses were preregistered on 25th of September 2019. For ease of reference, this report is appended to the preregistration document. The data and code are available in the OSF repository (folder *AdditionalAnalyses*, unless otherwise specified).

We have noticed and corrected several mistakes in our dataset. Four coins had wrong information on colour, seven on sizes, and two on designs. During data collection for new double coding, we noticed that there were more recent coin designs issued for Netherlands Antilles guilder (two coins), Uruguayan peso (4 coins), and Tajikistani somoni (5 coins) so we have updated them. Colours and sizes of these coins remained the same, except for four coins of Tajikistani somoni, whose sizes also changed, and were updated accordingly.

4.1. Designs similarity measure

We asked two independent coders to compare the photographs of 950 coin pairs (both sides of each coin) and assess how different are their designs (disregarding all other properties and inscriptions, see section 3.1.1). The coders were blind to the predictions. The task was to rate the difference/similarity between the designs on both sides of a pair of coins based on a six-point scale (0 = completely identical - 5 = completely different). The original coding sheets and the code can be found in the *DesignSimilarityCoding* folder in the OSF depository. The coding sheets were updated to include the changes in the dataset (see above). An inter-rater reliability test (Cohen's weighed Kappa for two coders), using the weights equal to the points on the scale (0-5) resulted in a Kappa of 0.59 ($z = 30.2$, N subjects = 950). A repeated test with squared weights produced a slightly higher Kappa of 0.75 ($z = 25.1$, N subjects = 950). Although these Kappa values indicate a moderate agreement, both values are below our preregistered threshold of 0.80, which means we did not get a reliable ordinal scale to use in the further analyses (see sections 3.1.1, 3.3.1.a and 3.4.2).

Even though we had only two coders, the considerable level of disagreement between them calls into question the use the similarity scale to reliably assess the differences between the coins. Interestingly, their answers do not tend to be polarised on both extremes, but rather skewed towards the "identical" end of the scale (0), suggesting that the coders were more certain in determining whether the two designs were identical or not, but it was more difficult for them to decide *how different*. If we convert the scaled coding into binary coding (0 = designs are identical, 1 = designs are different), by replacing all ratings larger than 0 with 1, we get an unweighted Kappa of 0.897 (z = 27.7, N = 950), the coders disagreeing in only 4% of the cases.

In the following analyses, we will use both measures of design distinctiveness: our original binary measure, based on the coin design descriptions provided by the sources (see section 1.5.1), and the new binary measure (converted scaled coding, described above), a product of image comparison. We will perform the relevant analyses with both measures. The differences in designs for the pairs the coders disagreed upon will be treated as NA. This means that, when using the "old" measure, 7 pairs the original coders disagreed upon will be omitted, and the models will run on the dataset of 943 pairs. Similarly, when using the "new" measure, we will exclude the 40 pairs the new coders disagreed upon, and run the models on the pairwise dataset of 910 pairs.

4.2. Repeated preregistered analyses with values standardized across currencies

We replicated our analyses using the value of each coin converted to US dollars, in addition to the coin values expressed as multiples of the smallest coined denomination in a currency ("Smallest Coins"). Our methods stayed the same as in the originally preregistered and reported analyses, unless otherwise specified.

4.2.1. Prediction 1: Value differentials predict differences in coin designs

In order to make sure that the corrections to the dataset have not affected the previously reported results, we first repeated our analysis with the original parameters ("old" differences in designs and values in "Smallest Coins"), on the corrected dataset. The results remained unchanged (compare section 2.2.1.b).

We performed three additional tests of this prediction: first, keeping the old binary differences in designs, but introducing the new value differentials in US dollars, second, with new binary differences in designs and old value differentials (in "Smallest Coins"), and third, with new design and value differentials. All three tests were performed after excluding the currencies whose coins designs are either all the same or all different, as in the original test. These tests replicated our original findings, suggesting that the pair of coins of adjacent value is more likely to have different designs as the value differential between them increases. All analyses produced a positive estimate for the value differentials as a predictor for design distinctiveness, and all were significant except for the test with simple value differentials in US dollars and the old differences in designs. In all cases, log-transforming the predictor improved its significance and the model performance (see **Table 9** below).

value differentials format	**designs similarity coding**	**dataset (N)**	**AIC comparison with null model (anova test)**	**estimate for predictor (log-transformed value differentials)**
"Smallest Coins"	old (descriptions)	386 pairs 64 currencies	Δ AIC = 17.09, χ2=19.09, p < 0.0001	β. = 0.308, z = 4.162, p < 0.0001
US dollars			Δ AIC = 5.86, χ2=7.86, p = 0.005	β. = 0.171, z = 2.617, p = 0.009
"Smallest Coins"	new (pictures)	373 pairs 65 currencies	Δ AIC = 31.42, χ2=33.42, p < 0.0001	β. = 0.422, z = 5.290, p < 0.0001
US dollars			Δ AIC = 16.86, χ2=18.85, p < 0.0001	β. = 0.284, z = 3.850, p = 0.0002

Table 9: Model comparisons and the effect size estimates for the effect of log-transformed value differentials upon design distinctiveness

4.2.2. Prediction 2: Value differentials predict differences in coin sizes

Here again we found it necessary to first replicate our original results after correcting the mistakes concerning sizes of 11 coins. We ran this analysis on the full pairwise dataset, after merging the variants of the same currencies into a single currency (euro and Pacific franc variants), which resulted in a dataset of 790 coin pairs, belonging to 159 currencies. The test showed that these corrections did not change the pattern of results reported in our original analyses (compare section 2.2.2.b).

We followed the same methods for the repeated analysis, only this time we used value differentials expressed in US dollars instead of "Smallest Coins". In addition to the preregistered models with log-transformed value differentials, we ran the models with simple value differentials as predictors, but neither managed to significantly improve on the null model (for the model with simple predictor, ΔAIC = 1.45, $\chi^2 = 3.45$, $p = 0.06$; for the log-transformed predictor ΔAIC = -0.76, $\chi^2 = 1.24$, $p = 0.266$). Excluding the outliers did not change the results; neither did considering only pairs that do not differ in colour.

4.2.3. The relationship between size and value

We repeated the post-hoc analysis, which was testing the relationship between sizes and values of single coins, rather than coin pairs. Here again we merged the euro currencies and the Pacific franc variants, which resulted in a dataset of 949 coin denominations belonging to 159 currencies. The repeated test with the coin values in "Smallest Coins" matched the original results (compare section 2.2.3). Introducing the values converted to US dollars has produced similar results. Model with the log-transformed predictor outperformed the null model and the model with the simple predictor, indicated by a significantly lower AIC score ($\Delta AIC_{null:logtransf.}$= 515.74, χ^2 = 517.74, p < 0.0001). The estimate for the effect of value is positive and significant for both models, although the significance is much higher when the predictor is log-transformed (t-value = 33.77). The results hold after the exclusion of outliers (N = 942 pairs, 159 currencies).

4.3. Additional prediction: Value differentials predict differences in colour

We tested an additional prediction, assuming the coins in a pair to be more likely to differ in colour as their value differentials increase (see section 3.4.1). The analysis was carried out on the full dataset of coin pairs (N = 950) belonging to 182 currencies. First, we ran and compared three models using the predictor (difference in value) expressed in "Smallest Coins", and then we ran the same models and model comparison replacing the predictor with the difference in value standardised in US dollars.

In the analysis including the predictor based on the "Smallest Coins", the "simple" model with the predictor required rescaling of the predictor variable to converge. This model did not improve on the null model ($\Delta AIC_{null:simple.}$= -1.13, χ^2 = 0.866, p = 0.352). Log-transforming the predictor, however, significantly improved the null model ($\Delta AIC_{null:logtransformed}$= 39.30 χ^2 = 41.299, p < 0.0001). The log-transformed predictor had a significant positive estimate (β = 0.276, z-value = 5.981, p < 0.0001), confirming our prediction and suggesting that the pair of coins adjacent in value, belonging to the same currency, is more likely to be of different colour as the difference in value between the coins increases (see **Figure 6**). This relationship is more likely to be non-linear.

Replacing the value differentials expressed in "Smallest Coins" with the differentials expressed in US dollars produced different results. Both models with predictors significantly improved on the null model, but the simple model outperformed the model with log-transformed predictor ($AIC_{null:simple.}$= 40.53, $\Delta AIC_{null:logtransformed}$ = 25.88).

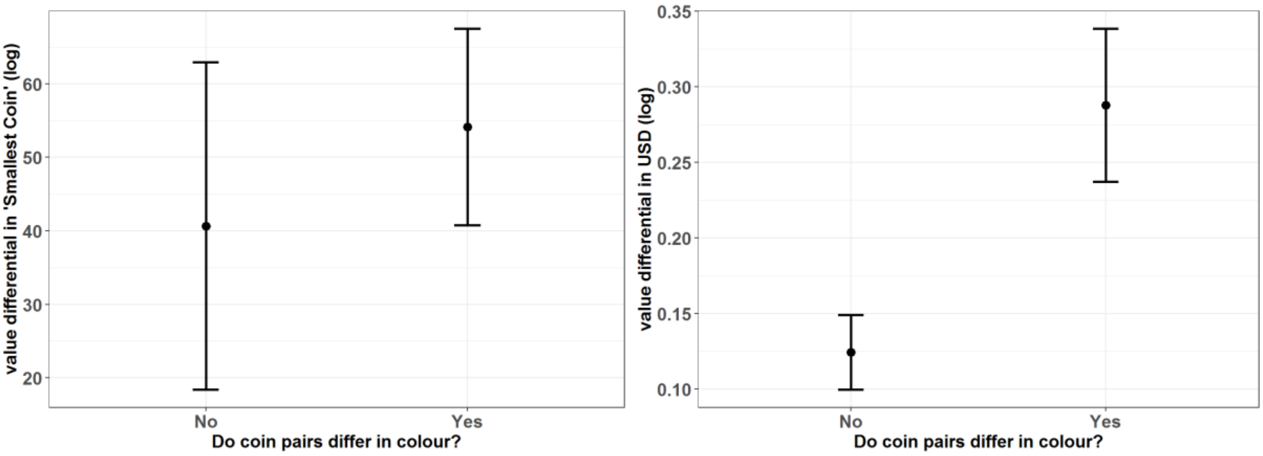

Figure 6: In pairs of coins with higher value differentials, coins are more likely to be of different colour. The points represent mean value differentials for the coin pairs that do not differ in colour and the ones that do. The error bars stand for 95% confidence intervals. The plot on the left is the result of the test with value differentials expressed in "Smallest Coins", and the plot on the right the result of the test with the differentials in US dollars.

4.4. Testing the joint effect of the different coin properties on coin value

We were encouraged to explore the possibility that multiple coin properties are correlated and the changes in these properties together signal the value differentials between the coins in a currency. We constructed two models with value differentials as dependent variables: a simple one with the "raw" value differentials between the adjacent pairs of coins, and the other predicting the log-transformed differentials. Both models included the differences in designs, sizes and colours as predictors, as well as two interaction effects (see section 3.4.2). We ran these models using both types of value differentials (in "Smallest Coins" and US dollars), and both versions of design similarity coding ("old" based on descriptions and "new" based on pictures).

4.4.1. Models with old designs similarity coding

For the models including the "old" differences in designs, we omitted the pairs of coins our coders disagreed upon, and ended up with the dataset of 943 pairs belonging to 182 currencies. We first ran two models with value differentials in "Smallest Coins", then again with value differentials in US dollars. The significant results (t-value above +/- 1.96, indicating 95% confidence interval) are summarised in **Table 10** below.

value differentials format	dependent variable (value differentials)	significant results	
"Smallest Coins"	simple	/	
	log-transformed	differences in designs	β = 0.442, t = 3.010
		differences in colour	β = 1.138, t = 5.608
		diff.designs : diff.colour	β = -0.570, t = -2.543
US dollars	simple	differences in colour	β = 0.208, t = 4.038
		diff.size : diff.colour	β = 0.032, t = 3.142
	log-transformed	differences in designs	β = 0.678, t = 3.879
		differences in colour	β = 1.292, t = 6.115
		diff.designs : diff.colour	β = -0.664, t = -2.826

Table 10: Significant results for the joint models predicting the value differentials from coin properties. The tests were performed with "old" designs similarity coding, on a dataset of 943 pairs belonging to 182 currencies.

The simple model predicting non-transformed value differentials expressed in "Smallest Coins" had no significant estimates of fixed effects, and all exhibited high standard error values. The comparison with the null model, including only the dependent variable (simple value differentials) and the random effect for currency, showed that predictors failed to improve the model (Δ AIC = -3.97). The simple model predicting the value differentials in US dollars, however, shows a significant positive fixed effect of differences in colour and a significant positive interaction effect between the differences in sizes and colours.

Two models predicting the log-transformed value differentials in "Smallest Coins" and US dollars both had significant positive estimates for the effects of differences in designs and colours, and a significant negative estimate for the interaction between these two properties. This might suggest that, if two coins in a pair have different designs *and* differ in colour, their value differentials are likely to be *smaller*. In other words, either a difference in designs or colours should be enough to indicate an increase in value differentials between the coins in a pair – a combination of the two properties is not only redundant but also potentially confusing.

4.4.2. Models with new designs similarity coding

We repeated the analysis using “new” differences in designs. The pairs our coders disagreed upon were omitted, which gave us a dataset of 910 pairs belonging to 181 currencies. The significant results are reported in **Table 11** below.

value differentials format	dependent variable (value differentials)	significant results	
“Smallest Coins”	simple	/	
	log-transformed	differences in designs	β = 0.590, t = 3.842
		differences in colour	β = 1.090, t = 4.658
US dollars	simple	differences in colour	β = 0.249, t = 4.126
		diff.size : diff.colour	β = 0.029, t = 2.798
	log-transformed	differences in designs	β = 0.837, t = 4.692
		differences in colour	β = 1.187, t = 4.921

Table 11: Significant results for the joint models predicting the value differentials from coin properties. The tests were performed with “new” designs similarity coding, on a dataset of 910 pairs belonging to 181 currencies.

These results match well with the results of the tests performed with the old designs similarity coding (see above). A notable exception is in case of the two models predicting the log-transformed value differentials, where the previously significant negative interaction between the differences in designs and colours is no longer significant.

This exploratory analysis has shown some interesting patterns, but it was investigating the connection between the coin properties and values from a different angle than our original predictions. The log-transformed value differentials between the adjacent pairs of coin denominations seem to be better represented by the differences in coin designs and colours, whereas the differences in size do not seem to be a good predictor of value differentials. This picture matches well the findings of our preregistered predictions. The interaction effects are difficult to interpret, as they are inconsistent between different tests.

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Zusammenfassung

Die Erfindung des Münzgeldes hatte einen signifikanten Einfluss auf die Wirtschaftsgeschichte durch die Einführung eines praktischen und allgemeinen Tauschmittels, dessen Wert von einer politischen Behörde reguliert und gesichert ist. Die Münzen agieren als materielle Darstellungen des Geldwertes. Um als Zahlungsmittel verwendet zu werden, müssen Münzen von ihren Benutzern als gültig und vertrauenswürdig anerkannt werden. Durch die Kombination von ausgewählten Materialeigenschaften, Inschriften und Bildern, bilden Münzen ein System von Symbolen, welches auf das Speichern und Übermitteln von, vor allem wirtschaftlichen, Informationen spezialisiert ist. Das Ziel dieser Dissertation war es zu untersuchen wie Informationen in Münzen kodiert werden, und zu verstehen, auf welche Weise die Entwicklung der Münzen als Informationssystem durch historische Dynamik und menschliche Kognition beeinflusst wurde. Die Fragen wurden in der vorliegenden Arbeit im Rahmen von drei Studien untersucht.

Die erste Studie konzentriert sich auf Münzen griechischer Stadtstaaten und anderer mediterraner Zivilisationen, welche zwischen Ende des 7. und Ende des 1. Jh. v. Chr. geprägt wurden. Das Ziel war es herauszufinden, wie die sich verändernden politischen und wirtschaftlichen Umstände dieser Zeit die Verwendung von Münzbildern als Zeichen des Prägeherrn und Geldwertes beeinflusst haben. Der Informationsgehalt von Münzbildern wurde mittels informationstheoretischer Methoden gemessen. Die Ergebnisse der statistischen Auswertungen zeigten, dass Münzbilder im Laufe der Zeit an Aussagekraft gegenüber dem Münzwert gewannen. Allerdings hat politische Konsolidierung und die Verbreitung von Münzbildern über unterschiedliche Städte ihren Informationswert als Symbole eines bestimmten Prägeherrn vermindert.

Die zweite Studie diskutierte die Vorteile und Herausforderungen von quantitativen Herangehensweisen an kulturelle Daten und präsentierte aktuelle Entwicklungen in der Digitalisierung und Standardisierung innerhalb der Geisteswissenschaften mit einem Fokus auf Münzikonographie. Die Bedeutung konsistenter und standardisierter Datenformate wurde am Beispiel des Datensatzes, der für die erste Studie erstellt wurde, dargestellt. Obwohl die informationstheoretischen Auswertungen belastbar gegenüber Änderungen in der Granularität der Münzbildkodierung blieben, zeigte sich, dass eine allgemeine, auf grundlegende Eigenschaften konzentrierte, den Detailgrad begrenzende Kodierungsvariante

die bevorzugte Option für standardisierte Beschreibungen ikonografischer Daten ist. Damit wird die Interoperabilität und Kompatibilität dieser Daten für statistische Analysen ermöglicht.

Die dritte Studie untersuchte die Darstellung und Wahrnehmung des Geldwertes in den Eigenschaften zeitgenössischer Münzen. Es wurde erwartet, dass zunehmende Wertunterschiede zwischen benachbarten Nominalen einer Währung durch vergleichbare Unterschiede in Münzbildern, Münzgrößen und Metallfarben gekennzeichnet sind. Die Ergebnisse zeigten, dass Münzbilder und Metallfarben dazu tendieren, größere Wertunterschiede deutlicher hervorzuheben. Andererseits wurde festgestellt, dass die Durchmesser der Münzen absolute Werte von Nominalen darstellen, sodass Münzen mit höherem Wert im Durchschnitt auch größer sind. Das Verhältnis von Münzeigenschaften zu Werten spiegelt sich auf einer logarithmischen Skala wider, was darauf hindeuten könnte, dass der menschliche Verstand Geldwerte ähnlich wie andere numerische Größen verarbeitet.

Diese Dissertation zeigt, wie man die Struktur und Entwicklung von Münzen in einem interdisziplinären Rahmen und mit quantitativen Methoden untersuchen kann, indem Erkenntnisse aus der evolutionären und kognitiven Anthropologie in Kombination mit Informationstheorie angewendet werden. Die zunehmende Verfügbarkeit von professionell kuratierten digitalen Sammlungen eröffnet weitere Möglichkeiten zur Entwicklung quantitativer Ansätze, die notwendig sind, um die Prozesse welche die beobachteten Muster in kulturellen Daten bildeten, richtig zu interpretieren. Diese Untersuchungen ergänzen einerseits die Forschung in Numismatik und Wirtschaftsgeschichte zu den Ursprüngen und der Entwicklung der Münzprägung, und erhellen andererseits die Möglichkeiten, historische Artefakte zu verwenden, um großräumige Muster in der Entwicklung und Übertragung kultureller Eigenschaften zu ermitteln.

Summary

The invention of coined money significantly changed economic history, by introducing a convenient and universal medium of exchange, whose value is regulated and guaranteed by a political authority. Coins function as physical representations of monetary value. In order to be used as a means of payment, they need to be recognized as valid and trustworthy. Combining carefully designed material features with inscriptions and images, coins form a system of symbols that store and transmit information, primarily of an economic nature. The aim of this thesis was to investigate how coins encode information, and to understand how historical dynamics and human cognition shaped their evolution as an informational system. These questions were explored over three studies conducted as a part of this doctoral project.

The first study focused on the ancient coins of Greek polities and other Mediterranean civilizations, issued from the end of the 7th to the end of the 1st century BCE. It investigated how the changing political and economic circumstances of this period influenced the informative role of graphic designs as marks of issuing authority and monetary value. Information in coin designs was quantified using measures based on information theory. The analysis of diachronic trends showed that coin designs became increasingly informative about the coins' value, while the political consolidation and diffusion of images reduced their informational value as symbols of a particular issuing authority.

The second study discussed the advantages and challenges of quantitative approaches to cultural data, and presented current advancements in digitization and standardisation in the humanities, with a focus on coin iconography. The importance of consistent and standardized data formats is illustrated on the example of the dataset constructed for the previous study. While measures based on information theory were shown to be robust to changes in the granularity of design coding, a generalized coding focused on basic characteristics and limiting the level of detail is found to be a preferred option for standardized descriptions of iconographic data, ensuring their interoperability and compatibility with statistical analyses.

The third study examines the representation and perception of monetary value in the properties of contemporary coins. Increasing differences in value between neighbouring coined denominations in a currency were expected to be marked by the similar differences in coin designs, sizes and colours. The results indicated that graphic designs and colours tend to mark larger differences in value more saliently. Coin sizes were found to indicate absolute

values of denominations, with coins of higher value on average also being larger. The correspondences between coin properties and values are reflected on a logarithmic scale, which might indicate that the human mind processes monetary values similarly to other numerical quantities.

This thesis shows how we can examine the structure and evolution of coins within an interdisciplinary framework, using quantitative methods, as well as insights from evolutionary and cognitive anthropology, combined with information theory. The increasing availability of expertly curated digital collections opens more possibilities for developing quantitative approaches necessary for proper interpretation of the processes which shaped observed patterns in cultural data. The approach taken in this project complements the research in numismatics and economic history on the origins and development of coinage, while also highlighting the possibilities of using historical artefacts to study large-scale patterns in the evolution and transmission of cultural traits.

Ehrenwörtliche Erklärung

Ich erkläre hiermit,

(a) dass mir die geltende Promotionsordnung bekannt ist,

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(c) dass mich folgende Personen bei der Auswahl und Auswertung des Materials sowie bei der Herstellung des Manuskripts unterstützt haben: Dr. Olivier Morin und Dr. James Winters.

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Jena, den 2. September 2020

Barbara Pavlek

Declaration of honour

Hereby I declare

(a) that I am aware of the applicable doctoral regulations,

(b) that I have written the doctoral thesis myself and that I have not taken any text sections from another author or from my own examination papers without indicating them and that I have indicated all tools and sources used by myself in this work,

(c) that I have mentioned all persons who have supported me in the selection and evaluation of the material as well as in the production of the manuscript,

(d) that I have not used the assistance of a doctoral advisor and that third parties have neither directly nor indirectly received monetary benefits from me for work that is related to the content of the submitted doctoral thesis,

(e) that I have not yet submitted this doctoral thesis as an examination paper for an academic examination,

(f) that I have submitted neither the same thesis nor an essentially similar thesis, nor a different thesis as a doctoral thesis at another university.

In Jena, 2 September 2020

Barbara Pavlek

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