

Standards and quantification of coin iconography: possibilities and challenges

Barbara Pavlek 

Minds and Traditions Research Group, Max Planck Institute for the Science of Human History, Germany

James Winters

Collective Computation Group, School of Collective Intelligence, UM6P, Ben Guerir, Morocco

Olivier Morin

Département d'études cognitives, Institut Jean Nicod, ENS, EHESS, CNRS, PSL University, UMR 8129, France and Minds and Traditions Research Group, Max Planck Institute for the Science of Human History, Germany

Abstract

The use of digital technologies and big data in the humanities and social sciences provided many opportunities for cultural heritage management and research, enabling data sharing and interdisciplinary collaborations. These developments increased the need for standardized data formats. General and domain-specific standards for describing and classifying cultural data, based on linked data principles, are developed to support increasingly numerous digital collections. However, the existing standards do not fully address the particular challenges concerning the standardized descriptions of images. Here we focus on ancient coins, an official image-bearing medium. We present current approaches to coin iconography, including the application of statistical measures to infer patterns in the use of images for communication. We discuss the importance of consistent, standardized data for quantitative research, and propose a generalized approach, focused on basic concepts and limiting the level of detail for the sake of simplicity, interoperability, and compatibility with statistical methods, as a necessary first step towards creating reliable iconographic standards.

Correspondence:

Barbara Pavlek, Max Planck Institute for the Science of Human History, Kahlaische Strasse 10, 07745 Jena, Germany.

E-mail:

pavlek@shh.mpg.de

1 Introduction

In recent years, the scope and volume of research on human history have 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 article, 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 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* (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), weights and measurements (Pondera, n.d.; Doyen, 2018), 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 analysing 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 1973–85), has been recently converted to a semantic ontology format (*Iconclass*, 2009). The Getty Research Institute developed several standardized vocabulary lists to support the linked databases of cultural data, including a thesaurus of iconographic terms (*The Getty Research Institute*, 2018). There were also initiatives to expand the CIDOC-Conceptual Reference Model 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 Tinitis, 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, 2015). 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.

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-Lyidian invention at the end of the 7th 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 5th 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; Gruber, 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.org, n.d.). As of yet,

standardized options for annotation of obverse and reverse design types are limited to marking the identity of the portrait head (object property 'nmo:hasPortrait', cf. Nomisma.org, n.d.). However, this marker is not consistently applied to all entries in the dataset. 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 their database of ancient and Byzantine weights, the *Pondera Online* team has replaced the error-prone and variable free-text descriptions of iconography with drop-down lists of predefined motifs nested in categories (e.g., animal, deity, human), while also allowing for detailed annotation by introducing additional fields describing the technique, position of the motif, etc. (Pondera, n.d.).

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. 77–8). 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 subcategories (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 (*Corpus Nummorum Online*, 2014–20). In a recent article, 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 a natural language processing-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 combating 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, 2018). 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 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 Callatay, 2018). Contemporary research tends to favour multi-disciplinary 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, 2018). 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 Callatay, 2018).

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 we can 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 (*Sylloge Nummorum Graecorum*, n.d.) and the *MANTIS* online database of the American Numismatic Society (2020), and prepared a corpus of unique coin types issued between c. 650 and c. 31 BCE, distributed approximately equally over eighteen time intervals. Time intervals were created using an unsupervised discretization algorithm (the *discretize* function from the *infotheo* package in R: Meyer, 2014; R Core Team, 2017; cf. Pavlek *et al.*, 2019). 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. For example, 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)¹.
- (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 consistently throughout the dataset, according to a pre-established standard, helps to avoid ambiguity and eliminates potential biases.

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 1](#) summarizes the differences between the ‘general’ and ‘specific’ coding approaches.

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

Table 1. Summary of coding guidelines for general and specific motif encoding

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 → rivergodAcheloo

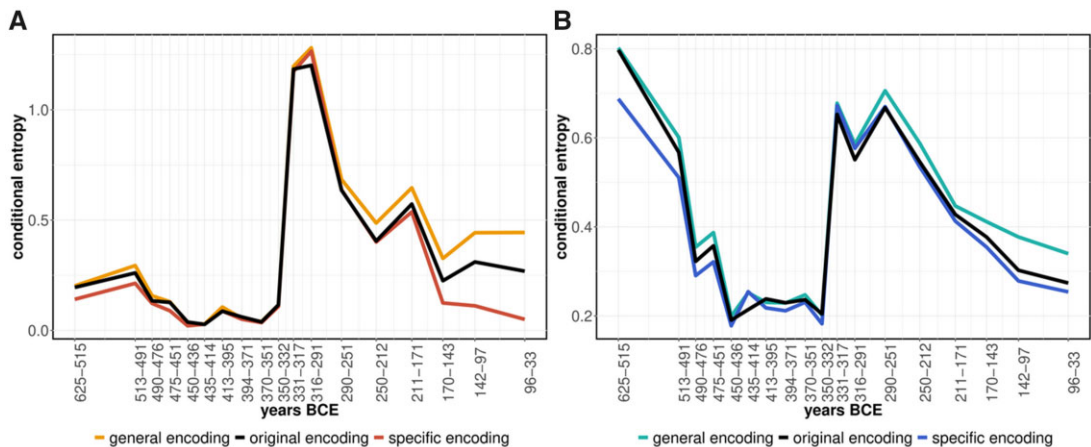


Fig. 1 Diachronic change of conditional entropy of authorities given designs (A) and denominations given designs (B) through eighteen time intervals, compared between the three encoding variants: original (black line), generalized, and specific (coloured lines). With time, coin designs become more informative 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

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 eighteen 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 1).

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 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

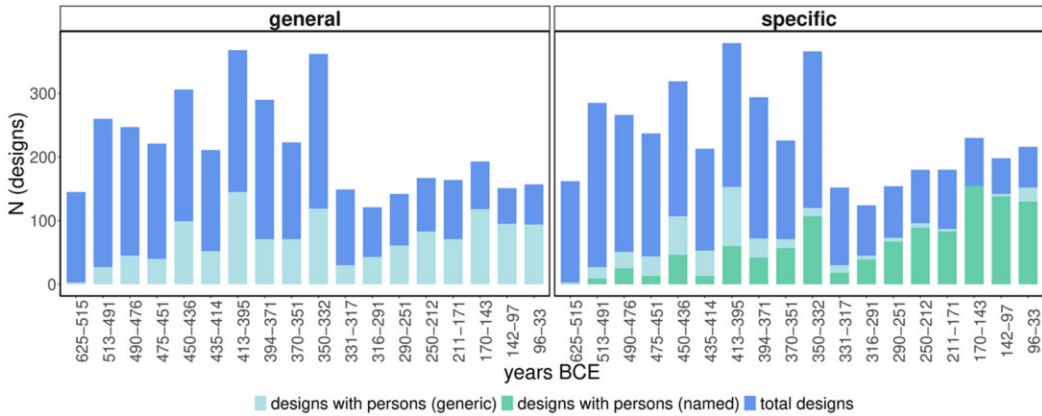


Fig. 2 Frequency distribution of unique design types (blue) in the 'general' and 'specific' datasets. The designs featuring generic persons ('king', 'nymph' etc.) are marked in light blue. The designs featuring named persons (e.g., 'Ptolemy I', 'nymphArethusa') are marked in green

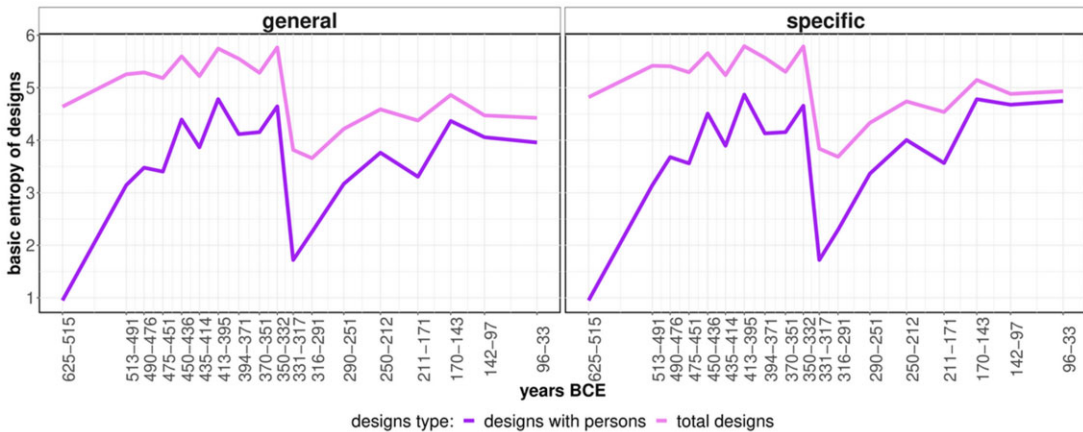


Fig. 3 Diachronic change of basic entropy of designs, measured for 'general' and 'specific' versions of the dataset through eighteen time intervals, separately for designs featuring persons (purple line), and all other designs in a period (pink line)

assigned the names based on the analogous coin types, verifying the suspicious cases in the referent literature (Head, 1911; Kraay, 1976). We strived to be systematic and consistent throughout the coding process, focusing primarily on resolving inconsistencies, and refrained from taking sides in complex numismatic debates on portrait attribution, which were beyond the topic of our study and our level of expertise.

Figure 2 presents the number of unique design types over eighteen 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), 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 1).

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 (Kraay, 1976, pp. 2–7; Carradice and Price, 1988, pp. 57–60). In 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.² 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.

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, makes 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 see the ‘big picture’ quantitatively, it is necessary to adopt some degree of abstraction and 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 that a generalized coding approach, focused on basic concepts rather than their specific manifestations and variations, is more suitable for quantitative analyses than a specific coding, capturing a greater level of detail, but introducing noise in statistical measures. Generalized coding could thus be regarded as a necessary first step towards creating reliable and generally applicable standards for iconographic descriptions.

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. Achieving this basic level of standardization for the majority of currently available digital collections would enhance the potential of this rich data in developing quantitative approaches for studying images, adding to our understanding of the ancient world. Expanding this basic standard by adding detailed information on

specific motif types and relationships between different motifs, as well as providing rich metadata and including competing expert interpretations of particular aspects of iconography would open further possibilities for conducting in-depth studies. 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.

Acknowledgements

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

Funding

This work was supported by the ‘Frontiers in Cognition’ EUR grant, ANR-17-EURE-0017 EUR.

Data Availability

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

References

- American Numismatic Society** (2020). *MANTIS: A Numismatic Technologies Integration Service*. *MANTIS*. <http://numismatics.org/search/department/Greek> (accessed 30 December 2020).
- Arachne**. *IDAI Objects*. <https://arachne.uni-koeln.de/druval/> (accessed 14 March 2020).
- ARIADNE**. *ARIADNEplus*. <https://ariadne-infrastructure.eu/about-ariadne/> (accessed 8 March 2020).
- Barker, E., Simon, R., Isaksen, L., de Soto Cañamares, P.** (2016). The Pleiades gazetteer and the Pelagios project. In Berman, M. L., Mostern, R. and Southall, H. (eds), *Placing Names: Enriching and Integrating Gazetteers*. Bloomington: Indiana University Press, pp. 97–109.

- Berezkin, Y. E.** (2015). Spread of folklore motifs as a proxy for information exchange: contact zones. *TRAMES*, XIX(1). <https://www.ceeol.com/search/article-detail?id=196617> (accessed 15 April 2020).
- Berners-Lee, T.** (2006). *Linked Data. The World Wide Web Consortium (W3C)*. <https://www.w3.org/DesignIssues/LinkedData.html> (accessed 13 March 2020).
- Bibliothèque nationale de France.** *BnF Archives et Manuscrits*. <https://archivesetmanuscrits.bnf.fr/> (accessed 15 April 2020).
- Binding, C. and Tudhope, D.** (2016). Improving interoperability using vocabulary linked data. *International Journal on Digital Libraries*, 17(1), pp. 5–21.
- Bodard, G., Cayless, H., Depauw, M., Isaksen, L., Lawrence, F., Rahtz, S.** (2017). Standards for networking ancient person data: digital approaches to problems in prosopographical space. *Digital Classics Online*, 3(2): 28–43.
- British Museum.** *British Museum Collection Online*. https://research.britishmuseum.org/research/collection_online/search.aspx (accessed 14 March 2020).
- Caccamo Caltabiano, M.** (2007). *Il Significato Delle Immagini: Codice E Immaginario Della Moneta Antica*. Reggio Calabria: Falzea.
- Caccamo Caltabiano, M.** (2018). Image as word and decoding coin images: the lexicon iconographicum numismatice classicae et mediae aetatis (LIN). In Iossif, P., de Callatay, F. and Veymiers, R. (eds), *TYTIOI. Greek and Roman Coins Seen through Their Images: Noble Issuers, Humble Users? Proceedings of the International conference organized by the Belgian and French Schools at Athens, 26–28 September 2012*. Liège, Belgium: Presses Universitaires de Liège, pp. 77–113.
- Caccamo Caltabiano, M., Salamone, G., Puglisi, M. et al.** (2013). DIANA: an approach to coin iconography according to time and space through digital maps. In Addison, A.C. et al. (eds.), *Proceedings of the 2013 Digital Heritage. International Congress*. Marseille: IEEE, pp. 413–16.
- Carboni, N. and de Luca, L.** (2019). An ontological approach to the description of visual and iconographical representations. *Heritage*, 2(2): 1191–210.
- Carradice, I.** (1978). *Ancient Greek Portrait Coins*. London: British Museum Publications.
- Carradice, I. and Price, M.** (1988). *Coinage in the Greek World*. London: Seaby.
- Celesti, A., Salamone, G., Sapienza, A., Spinelli, M., Puglisi, M., Caccamo Caltabiano, M.** (2017). An innovative cloud-based system for the diachronic analysis in numismatics. *Journal on Computing and Cultural Heritage*, 10(4): 23:1–23:18. 10.1145/3084546.
- CIDOC.** *CIDOC Conceptual Reference Model*. <http://www.cidoc-crm.org/> (accessed 13 March 2020).
- Classical Art Research Centre.** *Beazley Archive*. <http://www.beazley.ox.ac.uk/index.htm> (accessed 14 March 2020).
- Cooper, J. and Arandjelović, O.** (2020). Understanding ancient coin images. In Oneto L. et al. (eds), *Recent Advances in Big Data and Deep Learning*. INNS. Cham, Switzerland: Springer, pp. 330–40.
- Corpus Nummorum Online** (2014–20). *Corpus Nummorum Thracorum*. <https://www.corpus-nummorum.eu/thrace/about> (accessed 11 April 2020).
- David, R.** (2015). Towards a semantic content description for the visual arts. In Filipowska, A., Verborgh, R. and Polleres, A. (eds), *SEMANTiCS. Joint Proceedings of the Posters and Demos Track of 11th International Conference on Semantic Systems—SEMANTiCS 2015 and 1st Workshop on Data Science: Methods, Technology and Applications (DSci15)*. Vienna: CEUR Workshop Proceedings 1481, CEUR-WS.org, pp. 34–7.
- de Callatay, F.** (2018). Greek coin types in context: a short state of the art. In Iossif, P. and van de Put, W. (eds), *Greek Iconographies: Identities and Media in Context. Proceedings of a Seminar Organized by the Netherlands Institute at Athens and the Belgian School at Athens, 2016. Pharos*, 22(1). Athens: Peeters: 115–41.
- de Callatay, F.** (2011). Quantifying monetary production in greco-roman times: a general frame. In de Callatay, F. (ed.), *Quantifying Monetary Supplies in Greco-Roman Times. Pragmateiai*. Bari: Edipuglia, pp. 7–29.
- de Callatay, F.** (2018). L'iconographie des monnaies grecques: Brève historiographie et présentation des principales problématiques. In Iossif, P., de Callatay, F. and Veymiers, R. (eds), *TYTIOI. Greek and Roman Coins Seen through Their Images: Noble Issuers, Humble Users? Proceedings of the International conference organized by the Belgian and French Schools at Athens, 26–28 September 2012*. Liège, Belgium: Presses Universitaires de Liège, pp. 29–55.
- Dentamaro, F., Luca, P.G.D., Genco, L. et al.** (2007). A CIDOC CRM-based ontology system. In Clark J. T., and Hagemester E. M. (eds), *Digital Discovery. Exploring New Frontiers in Human Heritage. 34th Conference: Computer Applications and Quantitative Methods in Archaeology, Fargo, United States, April 2006*. Budapest: Archaeolingua, pp. 437–44.
- Doerr, M., Gradmann, S., Hennis, S., Isaac, A., Meghini, C., de Sompel, H.V.** (2010). The Europeana Data Model

- (EDM): object representations, context and semantics. In *Proceedings of the World Library and Information Congress: 76th IFLA General Conference and Assembly*. Gothenburg: IFLA, pp. 1–12.
- Doyen, C.** (2018). The Pondera Online Database. In Del Corso, L. (ed.) *Proceedings of the 2018 IEEE International Conference on Metrology for Archaeology and Cultural Heritage*. pp. 227–232. <http://hdl.handle.net/2078.1/204159> (accessed 10 October 2020)
- Doyen, J.-M.** (2011). Cliométrie et numismatique contextuelle: compter et quantifier le passé? petite histoire de la méthode (1960–2011). *The Journal of Archaeological Numismatics*, 1: 9–46.
- Elkins, N. T.** (2009). Coins, contexts, and an iconographic approach for the 21st century. In von Kaenel, H.-M., and Kemmers, F. (eds), *Coins in Context I: New Perspectives for the Interpretation of Coin Finds: Colloquium Frankfurt a.M., 25–27 October 2007. Studien zu Fundmünzen der Antike*, 23. Mainz: Von Zabern, pp. 25–41.
- Elliott, T., Bodard, G. and Cayless, H.** (2006). *EpiDoc: Epigraphic Documents in TEI XML*. *EpiDoc*. <http://epidoc.stoa.org/>. (accessed 3 September 2020)
- Elliott, T., Heath, S. and Muccigrosso, J.** (2014). Current practice in linked open data for the ancient world: prologue and introduction. *ISAW Papers*, 7. <http://dlib.nyu.edu/awdl/isaw/isaw-papers/7/elliott-heath-muccigrosso/>. (accessed 11 March 2020)
- Europeana.** *Europeana Pro*. <https://pro.europeana.eu/about-us/mission> (accessed 4 May 2020).
- Faucher, T.** (2018). Les types monétaires chez les lagides. In Iossif, P., de Callataÿ, F. and Veymiers, R. (eds), *ΤΥΠΟΙ. Greek and Roman Coins Seen through Their Images: Noble Issuers, Humble Users? Proceedings of the International conference organized by the Belgian and French Schools at Athens, 26–28 September 2012*. Liège, Belgium: Presses Universitaires de Liège, pp. 239–53.
- Forkel, R., List, J.-M., Greenhill, S.J. et al.** (2018). (1) Cross-linguistic data formats, advancing data sharing and re-use in comparative linguistics. *Scientific Data*, 5(1): 1–10.
- García, P. G., Gozalbes, M. and Ripollès, P. P.** (2019). Numismatic catalogues and digital humanities. In Maráz K. (ed.), *Mikulovské kolejni kabinety pomocných věd historických II: sborník z mezinárodní konference Ztráty a nálezy v pomocných vědách historických konané 18. a 19. října 2017 v Mikulově*. Brno: PhDr. Ivo Sperát, pp. 16–31.
- Gartner, R.** (2019). Towards an ontology-based iconography. *Digital Scholarship in the Humanities*, 35: 43–53.
- Gruber, E.** (2019). NUDS: first formal release of NUDS. Zenodo. 10.5281/zenodo.2536305 (accessed 9 March 2020)
- Gruber, E.** (2010). Encoded archival description for numismatic collections. In Frischer, B., Webb Crawford, J. and Koller, D. (eds), *Making History Interactive. 37th Conference: Computer Applications and Quantitative Methods in Archaeology, Williamsburg, Virginia, USA, 22–26 March 2009*. Oxford: Archaeopress, pp. 98–105.
- Gruber, E., Heath, S., Meadows, A., Pett, D., Tolle, K., Wigg-Wolf, D.** (2013). Semantic web technologies applied to numismatic collections. In Earl, G. et al. (eds), *Archaeology in the Digital Era II. 40th Conference: Computer Applications and Quantitative Methods in Archaeology, Southampton, 26–29 March 2012*. Amsterdam: Amsterdam University Press, pp. 264–74.
- Gruber, E. and Smith, T. J.** (2015). Linked open greek pottery. In Giligny, F. et al. (eds), *21st Century Archaeology. Concepts, methods and tools. 42nd Annual Conference: Computer Applications and Quantitative Methods in Archaeology, Paris 1 Panthéon-Sorbonne University, 22–25 April 2014*. Oxford, UK: Archaeopress, pp. 205–14.
- Head, B. V.** (1911). *Historia Numorum, a Manual of Greek Numismatics*. 2nd edn. Oxford: Clarendon Press.
- Heath, S.** (2018). SPARQL as a first step for querying and transforming numismatic data: examples from nomisma.org. In Meadows, A., Duyrat, F. and Glenn, S. (eds), *Alexander the Great. A Linked Open World*. Bordeaux: Ausonius Éditions, pp. 35–52.
- Hughes, J. M., Foti, N.J., Krakauer, D.C., Rockmore, D.N.** (2012). Quantitative patterns of stylistic influence in the evolution of literature. *Proceedings of the National Academy of Sciences*, 109(20): 7682–6.
- Huvila, I.** (2019). Management of archaeological information and knowledge in digital environment. In Handzic, M. and Carlucci, D. (eds), *Knowledge Management, Arts, and Humanities*. IAKM. Cham, Switzerland: Springer, pp. 147–69.
- Iconclass.** (2009). <http://www.iconclass.nl/home> (accessed 9 March 2020).
- Iossif, P.** (2011). Seleucid religion through coins. Is it possible to quantify “iconography” and “religion”? in: de Callataÿ, F. (Ed.), *Quantifying Monetary Supplies in Greco-Roman Times, Pragmateiai*. Edipuglia, Bari, pp. 213–249.
- Iossif, P.** (2018). Divine attributes on Hellenistic coinages: From ‘noble’ to ‘humble’ and back. In Iossif, P., de

- Callataÿ, F. and Veymiers, R. (eds), *ΤΥΠΟΙ. Greek and Roman Coins Seen through Their Images: Noble Issuers, Humble Users? Proceedings of the International conference organized by the Belgian and French Schools at Athens, 26–28 September 2012*. Liège, Belgium: Presses Universitaires de Liège, pp. 269–95.
- Iossif, P. and van de Put, W.** (2018). Greek iconographies: meandering paths to understanding images. In Iossif, P. and van de Put, W. (eds), *Greek Iconographies: Identities and Media in Context. Proceedings of a Seminar Organized by the Netherlands Institute at Athens and the Belgian School at Athens 2016*. *Pharos*, 22(1). Athens: Peeters, pp. 1–8.
- Jarrett, J., Zambanini, S., Hüber-Mork, R., Felicetti, A.** (2012). Coinage, digitization and the world-wide web: Numismatics and the COINS project. In Nelson, B. and Terras, M. M. (eds), *Digitizing Medieval and Early Modern Material Culture*. Toronto: Iter, pp. 459–89.
- Karwiese, S.** (1991). The Artemisium coin hoard and the first coins of Ephesus. *Revue Belge de Numismatique et de Sigillographie*, 137: 1–28.
- Kemmers, F. and Myrberg, N.** (2011). Rethinking numismatics. *The Archaeology of Coins. Archaeological Dialogues*, 18(1): 87–108.
- Kerameikos.org** <http://kerameikos.org/> (accessed 8 March 2020).
- Kerschner, M. and Konuk, K.** (2020). Electrum coins and their archaeological context: The case of the artemision of Ephesus. In Wartenberg, U., van Alfen, P.G., Fischer-Bossert, W., Gitler, H., Lorber, C., Konuk, K. (eds), *White Gold: Studies in Early Electrum Coinage*, New York, NY: American Numismatic Society, The Israel Museum Jerusalem, pp. 83–190.
- Klimek, P., Kreuzbauer, R. and Thurner, S.** (2019). Fashion and art cycles are driven by counter-dominance signals of elite competition: Quantitative evidence from music styles. *Journal of The Royal Society Interface*, 16(151): 20180731.
- Klinger, P., Gampe, S. and Peter, U.** (2018). Semantic search based on natural language processing—a numismatic example. *Journal of Ancient History and Archaeology*, 5(3): 68–79.
- Kraay, C. M.** (1976). *Archaic and Classical Greek Coins*. London: Methuen.
- Krmniczek, S. and Elkins, N. T.** (2014). Dinosaurs, cocks, and coins: An introduction to ‘Art in the Round’. In Elkins, N. T. and Krmniczek, S. (eds), *‘Art in the Round’: New Approaches to Ancient Coin Iconography*. Tübingen: *Archäologische Forschungen*. Rahden, Westf: VML Vlg Marie Leidorf, pp. 7–22.
- Kurtz, D., Parker, G., Shotton, D.** et al. (2009). CLAROS—bringing classical art to a global public. In Roe, P. and Wallom, D. (eds), *Proceedings of the 5th IEEE International Conference on E-Science(e-Science 2009)*. Oxford: IEEE, pp. 20–7.
- LIMC France. *Lexicon Iconographicum Mythologiae Classicae***. <http://www.limc-france.fr/bases> (accessed 8 March 2020).
- List, J.-M., Greenhill, S. J. and Gray, R. D.** (2017). The potential of automatic word comparison for historical linguistics. *PLoS ONE*, 12(1): e0170046.
- Liuzzo, P. M.** (2014). The Europeana Network of Ancient Greek and Latin Epigraphy (EAGLE). ISAW Papers, 7. <http://dlib.nyu.edu/awdl/isaw/isaw-papers/7/liuzzo/> (accessed 11 March 2020)
- Lozano, J. S.** (2017). Digital Art History at the Crossroads, *kunsttexte.de - E-Journal für Kunst- und Bildgeschichte*, 4: 1–14.
- Manders, E.** (2012). *Coining Images of Power: Patterns in the Representation of Roman Emperors on Imperial Coinage, A.D. 193–284*. Leiden, The Netherlands: Brill.
- Meyer, P. E.** (2014). *Infotheo: Information-Theoretic Measures*. <https://cran.r-project.org/web/packages/infotheo/index.html>. (accessed 11 January 2018)
- Morin, O.** (2015). A plea for “shmeasurement” in the social sciences. *Biological Theory*, 10(3): 237–45.
- Müller, M. G.** (2011). Iconography and iconology as a visual method and approach. In Margolis, E. and Pauwels, L. (eds), *The SAGE Handbook of Visual Research Methods*. London: SAGE Publications Ltd, pp. 283–97.
- Nomisma.org. *Nomisma IDs***. <http://nomisma.org/browse> (accessed 27 April 2020).
- Nomisma.org**. <http://nomisma.org/>(accessed 8 March 2020).
- Noreña, C. F.** (2001). The communication of the emperor’s virtues. *The Journal of Roman Studies*, 91: 146–68.
- Noreña, C. F.** (2011). *Imperial Ideals in the Roman West: Representation, Circulation, Power*. Cambridge. New York, NY: Cambridge University Press.
- Panofsky, E.**(1939). *Studies in Iconology: Humanistic Themes in the Art of the Renaissance*. New York, NY: Oxford University Press.
- Pavlek, B., Winters, J. and Morin, O.** (2019). Ancient coin designs encoded increasing amounts of economic

- information over centuries. *Journal of Anthropological Archaeology*, **56**: 101103. 10.1016/j.jaa.2019.101103.
- Pelagios Network**. <https://pelagios.org/> (accessed 7 March 2020).
- Perseus Digital Library**. <http://www.perseus.tufts.edu/hopper/> (accessed 14 March 2020).
- Pondera**. *Pondera Online Database*. <https://pondera.uclouvain.be/> (accessed 10 November 2020).
- Puglisi, M.** (2014). An iconographic approach to coins through the DIANA Atlas: The case study of the subject 'shell' on Greek coins. In Elkins, N. T. and Krmnicek, S. (eds), *'Art in the Round': New Approaches to Ancient Coin Iconography*. *Tübinger Archäologische Forschungen*. Rahden, Westf: VML Vlg Marie Leidorf, pp. 69–88.
- R Core Team** (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Roberts, S. and Winters, J.** (2013). Linguistic diversity and traffic accidents: Lessons from statistical studies of cultural traits. *PLoS ONE*, **8**(8): e70902.
- Rowan, C.** (2012). *Under Divine Auspices: Divine Ideology and the Visualisation of Imperial Power in the Severan Period*. Cambridge; New York: Cambridge University Press.
- Sapienza, A.** (2017). Un nuovo metodo d'indagine scientifica dei documenti numismatici: DIANA (Digital Iconographic Atlas of Numismatics in Antiquity). Il caso studio della triskeles. *Revista Numismática Hécate*, **4**, pp. 266–76.
- Scheidel, W.** (2008). The divergent evolution of coinage in Eastern and Western Eurasia. In Harris, W. V. (ed.), *The Monetary Systems of the Greeks and Romans*. Oxford: Oxford University Press, pp. 267–86.
- Shannon, C. E. and Weaver, W.** (1949). *The Mathematical Theory of Communication*. Urbana: University of Illinois Press.
- Sigaki, H. Y. D., Perc, M. and Ribeiro, H. V.** (2018). History of art paintings through the lens of entropy and complexity. *Proceedings of the National Academy of Sciences*, **115**(37): E8585–94.
- Slingerland, E. and Sullivan, B.** (2017). Durkheim with data: The database of religious history. *Journal of the American Academy of Religion*, **85**(2): 312–47.
- Smith, D. A., Rydberg-Cox, J. A. and Crane, G. R.** (2000). The Perseus Project: A digital library for the humanities. *Literary and Linguistic Computing*, **15**(1): 15–25.
- Sobchuk, O. and Tinitis, P.** (2020). Cultural attraction in film evolution: The case of anachronies. *Journal of Cognition and Culture*, **20**(3–4): 218–37.
- Sproat, R.** (2014). A statistical comparison of written language and nonlinguistic symbol systems. *Language*, **90**(2): 457–81.
- Sylloge Nummorum Graecorum**. <http://www.sylloge-nummorum-graecorum.org/> (accessed 21 May 2018).
- Tehrani, J. J.** (2013). The phylogeny of little red riding hood. *PLOS ONE*, **8**(11): e78871.
- The Getty Research Institute** (2018). *Getty Vocabularies*. <http://vocab.getty.edu/> (accessed 9 March 2020).
- The Index of Medieval Art**. <https://theindex.princeton.edu/> (accessed 15 March 2020).
- Thonemann, P.** (2016). *The Hellenistic World: Using Coins as Sources*. Cambridge: Cambridge University Press.
- Tolle, K. and Wigg-Wolf, D.** (2015). Uncertainty handling for ancient coinage. In Giligny, F. et al. (eds), *21st Century Archaeology. Concepts, methods and tools. 42nd Annual Conference: Computer Applications and Quantitative Methods in Archaeology, Paris 1 Panthéon-Sorbonne University, 22–25 April 2014*. Oxford, UK: Archaeopress, pp. 171–79.
- Tolle, K., Wigg-Wolf, D. and Gruber, E.** (2018). An ontology for a numismatic: Island with bridges to others. In Matsumoto, M. and Uleberg, E. (eds), *Oceans of Data. 44th Conference: Computer Applications and Quantitative Methods in Archaeology, Oslo 30 March–3 April 2016*. Oxford: Archaeopress, pp. 103–8.
- Warburg Institute**. *Warburg Institute Iconographic Database*. https://iconographic.warburg.sas.ac.uk/vpc/VPC_search/main_page.php (accessed 15 March 2020).
- Watts, J., Sheehan, O., Bulbulia, J., Gray, R.D., Atkinson, Q.D.** (2018). Christianity spread faster in small, politically structured societies. *Nature Human Behaviour*, **2**(8): 559–64.
- Weir, R.** (2010). Interpretation and imitation of classical greek coin types. In Drexhage, H.-J., Rollinger, R., Mattern, T., Ruffing, K., Schäfer, C. (eds), *Marburger Beiträge Zur Antiken Handels-, Wirtschafts-Und Sozialgeschichte*, **28**, pp. 123–70.
- Wigg-Wolf, D. and Duyrat, F.** (2017). La révolution des linked open data en numismatique: Les exemples de Nomisma.org et Online Greek Coinage. *Archéologies Numériques*, **17**(1): 1–12.

- Winters, J., Kirby, S. and Smith, K.** (2015). Languages adapt to their contextual niche. *Language and Cognition*, 7(3): 415–49.
- Winters, J. and Morin, O.** (2019). From context to code: Information transfer constrains the emergence of graphic codes. *Cognitive Science*, 43(3): e12722.
- Youngblood, M.** (2019). Conformity bias in the cultural transmission of music sampling traditions. *Royal Society Open Science*, 6(9): 191149.
- Yucesoy, B., Wang, X., Huang, J., Barabási, A.-L.** (2018). Success in books: A big data approach to bestsellers. *EPJ Data Science*, 7(1): 1–25.
- Zaharieva, M., Kempel, M. and Zambanini, S.** (2007). Image based recognition of ancient coins. In Kropatsch,

W.G., Kempel, M., Hanbury, A. (eds), *International Conference on Computer Analysis of Images and Patterns*. Liège, Belgium: Springer, pp. 547–554.

Notes

- 1 Accessible online at: <http://numismatics.org/collection/> followed by the catalogue number (e.g., <http://numismatics.org/collection/1997.9.20>).
- 2 For recent examples of studies discussing iconographic representations on the coins issued by Roman emperors through the analysis of relative frequencies of particular coin types, cf. [Noreña, 2001, 2011](#); [Rowan, 2012](#); [Manders, 2012](#).