

# Identifying social learning between Roman amphorae workshops through morphometric similarity

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## Abstract

The aim of this study is to identify interaction dynamics within amphorae workshops in the Roman Empire. The Baetica province (currently Andalusia, southern Spain) hosted for almost 300 years a massive infrastructure that supplied olive oil to the Western provinces of Rome. A large number of workshops produced the same type of amphora to ship the product through maritime and riverine transport networks. Despite the amount of evidence, it is difficult to find an archaeological proxy able to tell us how these workshops were organised.

We apply here an evolutionary framework to understand potential links between workshops through morphometric similarities in the amphorae they produced. By exploring small yet statistical significant differences in the amphorae made in 5 different workshops the approach is able to identify how individual potters acquired and transmitted technical skills. Our approach applies multivariate statistical methods to cluster a variety of amphorae based on morphometric measurements. Other studies have developed similar approach to analyse handmade pottery but we show here that the method can be also applied to large-scale production of a standardized amphora type (i.e. Dressel 20).

Results suggest that morphometric similarity is inversely correlated with spa-

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tial distance between workshops. This outcome suggests that pottery-making techniques were transmitted through oblique transmission with little or no movement of potters between distant workshops.

The work also highlights that morphometric similarity may be an effective proxy to identify social learning dynamics even amongst workshops producing exactly the same amphoric type.

*Keywords:* Roman Empire; amphorae workshops; Dressel 20; social learning; cultural evolution

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## 1. Introduction

The archaeological record can help us identify the mechanisms by which humans learn from each other (Richerson and Boyd, 2005; Eerkens and Lipo, 2007). Cultural transmission dynamics can be identified by analysing archaeological proxies able to capture the distinct variability generated by different social learning mechanisms (Shennan and Wilkinson, 2001; Eerkens and Lipo, 2005; Gandon et al., 2014). This approach has been successfully applied to the material culture generated by small-scale societies but it has been seldom explored in the case of large-scale production (Shennan et al., 2015).

This paper explores the social dynamics of specialized production in the Roman Empire. We focus here on analysing large-scale production of a single amphoric type (Dressel 20) in a specific area. An evolutionary framework is used to identify social learning dynamics between pottery-makers (Shennan, 2008a; Mesoudi, 2015).

Following a large number of authors (Neff, 1992; Shennan, 2002; Bowser and Patton, 2008; Hosfield, 2009), pottery production can be learned by different modes of cultural transmission depending on the level of production in the communities. Vertical transmission is a mode of transmission whose teaching of the production is done from parents to offspring (biological transmission); oblique transmission from master to young generation of disciples while in horizontal transmission individuals teach pottery techniques to other individuals

within the same level and those workers spread the knowledge to their community (Cavalli-Sforza and Feldman, 1981; Acerbi and Parisi, 2006).

Given those mechanisms of transmission, artefact variation should also be  
25 affected by geographical distance (Björklund et al., 2010; Shennan et al., 2015;  
Van Strien et al., 2015). If vertical or oblique transmission are predominant  
then material culture should be similar in nearby groups with high degree of  
interaction (Hart, 2012). The underlying consequence is that it should be possi-  
ble to identify interaction between workshops by quantifying similarity amongst  
30 the amphorae they produced; if apprentices moved between distant workshops  
then no differences would be found on this proxy while a more strict oblique  
transmission would be revealed by distant workshops exhibiting less similarity.

The debate on social learning processes is hindered by the challenge of de-  
tecting the different modes of transmission in the archaeological record (Roux,  
35 2015). In the case of archaeology, several studies have analysed this process  
focused on the production of handmade pottery (Steele et al., 2010) or with  
stylistic variations (Neiman, 1995; Shennan and Wilkinson, 2001). Our work  
aims at identifying learning processes even in the case of the standardized mas-  
sive olive oil production common during the Roman Empire (Bevan, 2014).

40 Olive oil was one of the most important products of the Classical Medi-  
terranean world as it was used in almost all aspects of daily life including cooking,  
lightning and hygiene (Mattingly, 1988). The Baetica province (currently An-  
dalusia, southern Spain) developed a massive infrastructure of olive oil produc-  
tion to face the demands of the Roman Empire. The product was shipped in  
45 large amounts of amphorae to distant provinces all along the Western provinces.  
One of its most important clients was the Roman army as olive oil was supplied  
to tens of thousands of legionaries in places such as Britannia (Carreras Monfort,  
1998; Funari, 2005) and Germania (Remesal, 1986).

For this reason, this ancient province became an important support for the  
50 production and distribution of olive oil to the rest of the Empire during three  
centuries (Berni, 1998; Remesal, 1998; Chic, 2005). Baetica provided a strong  
connectivity through riverine transport that allowed inland producers to use

an important trade network through the Mediterranean and Atlantic (García Vargas, 2010). The exponential production growth required the creation of over  
55 a hundred amphora workshops supporting olive oil shipment. These workshops were located along the Guadalquivir river and its tributaries. The majority of amphorae produced in this area are classified as Dressel 20 type divided into a variety of subclasses (Martin-Kilcher, 1987; Berni, 2008). Dressel 20 was mostly used to transport olive oil for around 300 years in order to satisfy the demand  
60 within Roman Empire (Remesal, 1977).

The question about the organization of potters within Roman Empire remains under discussion due to the lack of archaeological evidence and written sources. Several studies have analysed amphorae using a diversity of approaches, from chemical analyses to large-scale distribution (Isaksen, 2006; Brughmans  
65 and Poblome, 2016; Rubio-Campillo et al., 2017). However, the structure of social learning that transmitted knowledge on how amphorae were made is still poorly understood. It still remains unknown whether these workshops were run by families or groups of owners without kinship. Did they have different traditions and apprentices worked in the place where they were trained? Did potters  
70 work in more than one workshop? Were changes in production decided by workshops or by external actors? All these questions are linked to the social learning processes that took place in the workshops. On the other hand, archaeological record shows this specialized production as highly organized both in terms of products and processes and with apparently few variations. The same type of  
75 amphorae was produced over 300 years while similar stamps and information was recorded on them (Remesal, 2004).

If the system was organised based on oblique transmission mechanisms with no potters moving to distant workshops then amphorae produced in nearby workshops might share more similar traits than with the rest of the production.  
80 On the other hand, if horizontal dynamics were common then this correlation with spatial coordinates should not be present as workers would share their methods.

The paper can be summarized as follows. The next section introduces the

dataset and the methods used to analyse it. Section three presents the results  
85 while the last part discusses the outcomes and highlights the main conclusions  
of the work.

## 2. Material and methods

### 2.1. Workshops

Our sample consisted of 413 Dressel 20 amphorae collected from the 5 Dressel  
90 workshops that have been more intensively excavated in the last decades. The  
workshops were located at Malpica, Cerro del Belén (hereafter, Belén) (Díaz  
Trujillo, 1992), Parlamento (García Vargas, 2000), Villaseca (García Vargas  
and Morena, forthcoming) and Las Delicias (Fernández et al., 2001; Mauné  
et al., 2014) (see Figure 1).

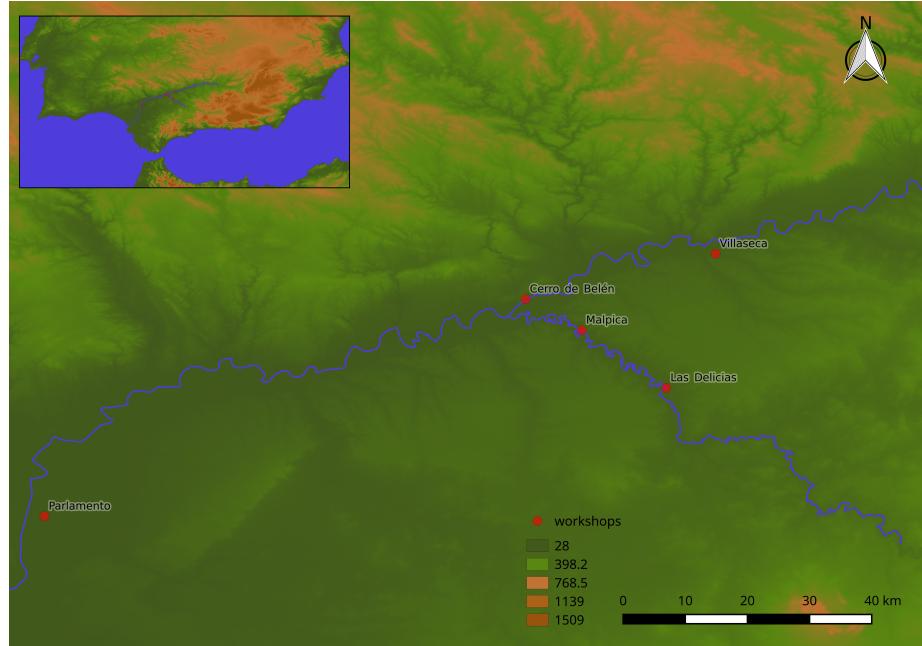


Figure 1: Map from Baetica province during the Roman Empire depicting the location of the 5 analysed workshops. Dressel 20 workshops were mostly distributed along the rivers Gualdalquivir and Genil.

95      The sample was roughly uniformly distributed amongst the 5 workshops (80-  
 100 samples for each of them). These workshops were distributed in a diversity of  
 locations therefore spatial dynamics could be potentially identified. All of them  
 had long work activity so differences in amphorae could display overlapping  
 temporal variation. This trait is reinforced by the fact that the Dressel 20  
 100 type remained almost unchanged over three centuries (Berni and García Vargas,  
 2016). We analysed Dressel 20 of the three most abundant variants in our  
 dataset spanning approximately three centuries (Dressel C, Dressel D, Dressel  
 E) (Martin-Kilcher, 1987; Berni, 2008). All the variants were found in the 5  
 workshops and, consequently, no intrinsic bias was generated by them.

105    *2.2. Spatial Distance*

The approach required us to compute a pairwise matrix of spatial distances  
 between workshops. All these workshops were located near a river as the am-  
 phorae were shipped by boat after being made and filled with olive oil. Given  
 the relevance of riverine transport it was decided that the best proxy for spatial  
 110 distance between workshops was the one observed following the river course, as  
 summarized in Table 1.

<b>Workshops</b>	Malpica	Belén	Villaseca	Las Delicias	Parlamento
Malpica	-	11	50	17	108
Belén	11	-	33	29	98
Villaseca	50	33	-	67	133
Las Delicias	17	29	67	-	126
Parlamento	108	98	133	126	-

Table 1: Distance matrix between workshops (in km.)

*2.3. Measurements*

Eight different measurements were taken from each amphora. The metrics  
 were focused on the rim sherds as this section presents the best preservation  
 115 for most archaeological contexts and they present good indicators of variation

(Berni, 2008). Other interesting proxies such as handles and bases were found in lesser quantities and for this reason they would be less appropriate for quantitative approaches due to low sample size. The measurements can be seen in Figure 2; they were divided into exterior diameter, inside diameter, rim height, 120 rim width, shape width, rim inside height, rim width 2 and protruding rim.

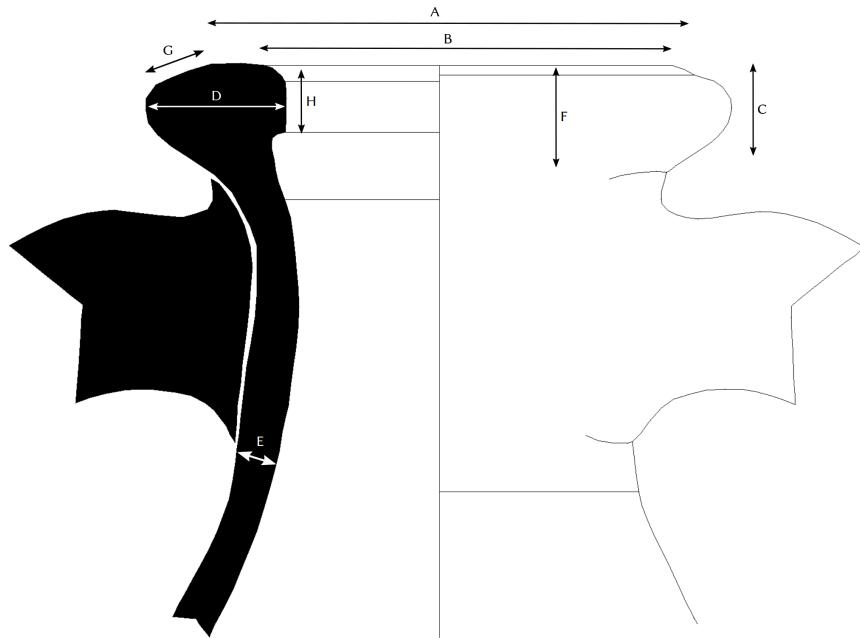


Figure 2: The 8 morphometric measurements taken for all amphorae. A: External diameter. B: Inside diameter. C: Rim height. D: Rim width. E: Shape width. F: Rim inside height. G: Rim width 2. H: Protruding rim.

#### 2.4. Exploratory Data Analysis

Principal Component Analysis (PCA) was used to explore the variation of measurements over the different workshops (Jolliffe, 2002). PCA is a common method in archaeology in scenarios studying within-sample variation (Shennan, 125 2008b; Li et al., 2014; Schillinger et al., 2016b). The method allowed us to visualize the dataset by focusing on a small number of Principal Components

(PCs) while retaining a majority of the variation which was in essence what we wanted to explore.

### *2.5. Morphometric similarity*

130 Exploratory Data Analysis was followed by the measurement of pairwise dissimilarity between the amphorae made in different workshops. The approach presented here is based on the idea that if most amphorae made in two workshops are difficult to distinguish then the workshops are making similar artefacts; on the other hand if the probability of distinguishing the production place of most 135 amphorae is high then there are remarkable morphometric differences between the objects. This goal could be achieved by 1) training a clustering algorithm with the dataset 2) using the model to predict the workshop of the same dataset and 3) computing a confusion matrix.

The choice of clustering method was Linear Discriminant Analysis (LDA). 140 The entire dataset was used both for the training and prediction steps as we were interested on how well workshop attribution could be predicted relying exclusively on morphometric measures. A Confusion Matrix was then computed as a quantification of the extent to what amphorae of different workshops can be identified. The Confusion Matrix computes this quantity as the number of misclassifications between each pair of groups in the dataset (i.e. the workshops). 145 This method has already been used in similar scenarios aiming at identifying differences in artefact production (Thorpe et al., 1984; Aguilera, 1998; Charlton et al., 2012). If the amphorae made in two workshops were easily confused then their average measures must be similar; on the other hand, if the rate of 150 misclassification between two workshops is very low then the amphorae made in these locations are distinctively different.

The diagonal of the confusion matrix (i.e. correct classifications) was removed and the number of confusions per each workshop was then divided by the total number to get the percentage of errors from a given workshops to the 155 rest of the sample. These values were finally normalized to generate a pairwise distance matrix of morphometric measurements.

## 2.6. Dissimilarity correlation

The last step of this method was the comparison of morphometric and spatial distance matrices. A significant correlation between these dissimilarity matrices would suggest processes of isolation-by-distance typical from oblique transmission.  
160

The evaluation of these two distance matrices (morphometric distance and spatial distance) was computed using a Mantel test. Mantel test evaluates the degree of pairwise correlation between two matrices and has been particularly useful in archaeology to explore the spatial dimension of cultural change (Mantel, 1967; Diniz-Filho et al., 2013; Crema et al., 2014).  
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## 3. Results

### 3.1. Principal Component Analysis

The loadings for the two main Principal Components of the dataset are listed  
170 in Table 2.

Variables	PC1	PC2
Exterior diameter	0.877	0.312
Inside diameter	0.404	-0.887
Rim height	-	-
Rim width	0.149	0.119
Shape width	-	-
Rim inside	-	-
Rim width 2	0.133	0.142
Protruding rim	-0.159	-0.272

Table 2: Two main Principal Components. Diameter values and the protruding rim seem to capture the majority of variation.

An exploratory visualization for these two main Principal Components can be seen in Figure 3. The plot suggests that each workshop exhibits slightly different dynamics for PC1 while PC2 is distinctively different for the two most

distant sites (Villaseca and Parlamento). Additionally, the first PC also tends  
<sup>175</sup> to display more similar values for amphorae made in nearby workshops such as Belén and Malpica. The exploratory analysis was also tested individually by Dressel 20 types in order to observe differences according to the chronology. A similar pattern is observed in Figure 4. The result suggests a noticeable variability between Dressel C and Dressel D and E but barely perceptible between  
<sup>180</sup> Dressel D and E.

### *3.2. Linear Discriminant Analysis*

LDA's prediction generated an accuracy of 56.6%. For this method the accuracy of the clustering algorithm is not as relevant as the distribution of errors which can be seen in the Confusion Matrix of Table 3. Each row of  
<sup>185</sup> the matrix represents the predicted class while each column represents the real class. The Confusion Matrix predicted the farthest workshop (Parlamento) with more correct classification than the other workshops that had problems to be distinguished.

	Belén	Delicias	Malpica	Parlamento	Villaseca
Belén	48	11	16	4	6
Delicias	10	81	24	8	0
Malpica	12	12	49	1	6
Parlamento	6	10	9	25	10
Villaseca	12	5	13	4	31

Table 3: Confusion Matrix of errors in predicted classifications between workshops. The sample analysed gave an accuracy percentage of 56.6% with p-value <0.01.

A tentative glance to these results suggest that workshops with a minor  
<sup>190</sup> spatial distance such as Malpica, Belén and Las Delicias made amphorae that are more difficult to distinguish due to their similarity. By contrast, workshops as Parlamento shows a minor misclassification coinciding with a higher spatial distance.

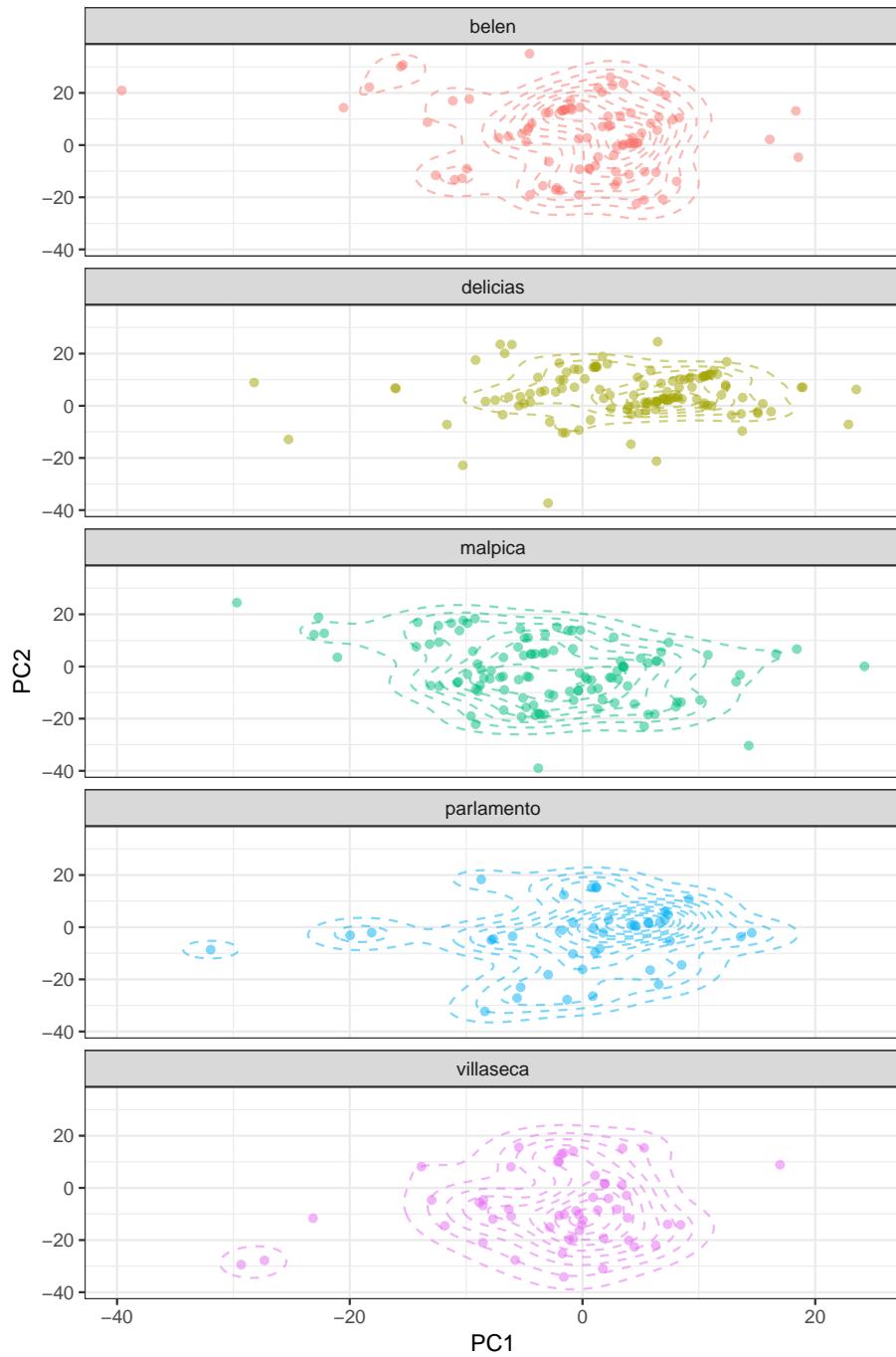


Figure 3: Scatter and density plot for the First and Second PCs. Sample is split by workshop

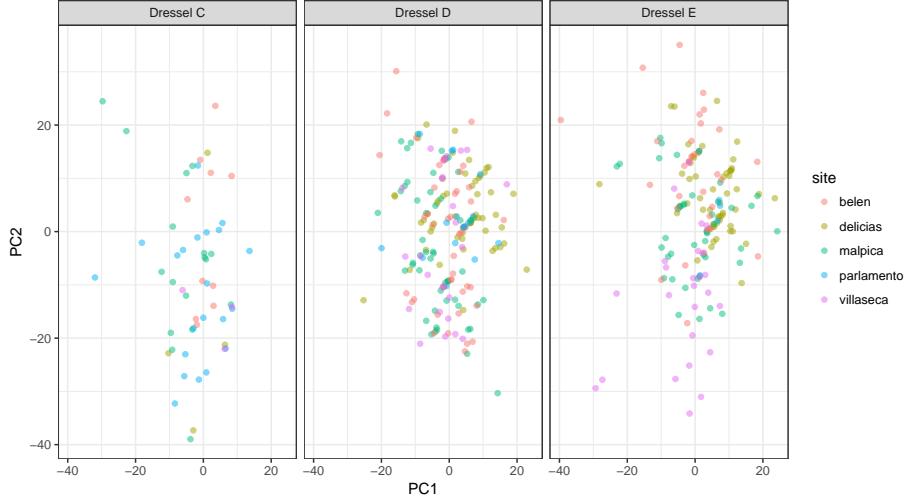


Figure 4: Scatter plot for the First and Second PCs. Sample is divided by Dressel 20 types

### 3.3. Mantel correlation test

195 Mantel test between morphometric and spatial dissimilarity matrices generated a correlation of 0.51 with p-value under 0.01. The analysis shows that morphometric distance of the amphorae are strongly correlated with the spatial distance of workshops. Accordingly closer workshops tend to be more similar than the rest: when geographic distance is low, as the example of Belén and  
 200 Malpica, the morphometric distance seems more similar whereas when distance is higher, as Parlamento, the morphometric distance displays differences with the rest of workshops. Thus, the results suggest that the variability on the making-techniques processes might depend on the spatial distance.

## 4. Discussion and Concluding remarks

205 Similarity on the making techniques processes amongst workshops shows an inverse correlation with spatial distance. The fact that isolation by distance can be identified suggests limited mobility strictly linked to nearby workshops. The analysed morphometric traits suggest that the similarity between amphorae decreases with the spatial distance between the workshops where they were

<sup>210</sup> produced. As a result, amphorae made in nearby workshops share more similar traits than amphorae made in distant workshops where contact was less frequent.

Horizontal transmission or high mobility do not seem to match with the results of the analysis. Scenarios with frequent contact between potters or workers moving from workshop to workshop would have generated larger homogeneity <sup>215</sup> in the technical practises with low intensity of isolation-by-distance processes. As a consequence, workshops sharing a network of potters would have employed the same production techniques, thus generating similar amphorae.

In addition, the variability on the morphological techniques between workshops does not suggest different groups of craft organization of making amphorae. <sup>220</sup> Neither any intentionality of modification or improvement of these techniques have been detected in the analysis.

Rather the results suggest that oblique transmission could be the main cultural mechanism to explain the variability between workshops. The different morphological traits amongst workshops seem to reveal low frequency of contact between potters from other workshops. The equilibrium of this dynamic for <sup>225</sup> a long time span (over three centuries) can be interpreted as a high-fidelity social learning mechanism transmitted within each one of the workshops (Schillinger et al., 2016a). The disciples could have remained working at the same workshops where they were trained. In other words, individuals would have copied <sup>230</sup> the same model of amphora from other individuals but unintentionally making small random errors in a same workshop. Hence, each workshop would produce the same amphora assemblages with different mutations caused by accumulating copying error transmitted by generations. These differences seem less remarkable when the production increases in order to satisfy the demand of the Roman Empire, then it tends to be more standardized. <sup>235</sup>

Despite these results the diversity of social learning processes is always complex. The transmission of technical skills during apprenticeship (master to disciples) and their limited mobility does not imply that horizontal transmission did not exist. It can be a mechanism where this process was initially led by <sup>240</sup> master to disciples in the same workshops but consequently this transmission

would be affected by the high demand of production promoting workers moving to other workshops and exchange ideas.

To conclude, the method presented here provides a framework to identify social learning mechanisms between production centres based on morphometric measurements of artefacts. The method has proven valuable even in the case of the highly standardized amphoric production of the Roman Empire.  
245 The suggested method could also offer a good comparison with other analytical methods such as archaeometry; we believe that a framework integrating and comparing multiple sources of evidence could be extremely effective on the process of characterization of production sites and places of consumption. Our analysis provides a useful guideline for the exploration of the social learning processes connected with amphora production in the Roman Empire. Hence, the results have lightened to understand the link between social learning and archaeological evidence in a diversity of scenarios.  
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260 Museum of Palma del Río (Reyes Lopera and Emilio Navarro), Museum of Córdoba and Museum of Seville for kindly allowing us access to their information. Data were collected, performed and analysed in R version 3.2.4. statistical language and implemented with the packages MASS, vegan and ggplot2 (Ripley et al., 2013; Oksanen et al., 2007; Wickham et al., 2016). Map was done by QGIS 2.18.15 'Las Palmas' with SRTM data Version 4.1 from CIAT-CSI SRTM website (<http://srtm.csi.cgiar.org>) (Jarvis et al., 2008).

Source code and datasets are freely available and can be downloaded from <https://github.com/Mcotsar/LearningBaetica>.

<sup>270</sup> **References**

- Acerbi, A., Parisi, D., 2006. Cultural Transmission Between and Within Generations. *Journal of Artificial Societies and Social Simulation* 9, 9. URL: <http://jasss.soc.surrey.ac.uk/9/1/9.html>.
- Aguilera, A., 1998. Análisis multivariable: una nueva vía para la caracterización cerámica. *Pyrenae* 29, 117–134.
- <sup>275</sup> Berni, P., 1998. Las ánforas de aceite de la Bética y su presencia en la Cataluña romana. volume 4. Col .lecció Instrumenta. Universitat de Barcelona.
- Berni, P., 2008. Epigrafía anfórica de la Bética. Nuevas formas de análisis. volume 29. Col .lecció Instrumenta. Universitat de Barcelona.
- <sup>280</sup> Berni, P., García Vargas, E., 2016. Dressel 20 (Guadalquivir Valley). URL: <http://amphorae.icac.cat/amphora/dressel-20-guadalquivir-valley>.
- Bevan, A., 2014. Mediterranean Containerization. *Current Anthropology* 55, 387–418. URL: <http://www.jstor.org/stable/info/10.1086/677034>, doi:10.1086/677034.
- <sup>285</sup> Björklund, M., Bergek, S., Ranta, E., Kaitala, V., 2010. The effect of local population dynamics on patterns of isolation by distance. *Ecological Informatics* 5, 167–172.
- Bowser, B.J., Patton, J.Q., 2008. Learning and Transmission of Pottery Style. Women's Life Histories and Communities of Practice in the Ecuadorian Amazon, in: Cultural transmission and material culture: Breaking down boundaries. The University of Arizona Press, pp. 105–129.
- <sup>290</sup> Brughmans, T., Poblome, J., 2016. Roman bazaar or market economy? Explaining tableware distributions through computational modelling. *Antiquity* 90, 393–408. URL: [http://www.journals.cambridge.org/abstract\\_S0003598X16000351](http://www.journals.cambridge.org/abstract_S0003598X16000351).

- Carreras Monfort, C., 1998. Britannia and the imports of Baetican and Lusitanian amphorae. *Journal of Iberian Archaeology* 1, 159–172.
- 300 Cavalli-Sforza, L.L., Feldman, M.W., 1981. Cultural transmission and evolution: a quantitative approach. Princeton University Press.
- Charlton, M.F., Blakelock, E., Martinón-Torres, M., Young, T., 2012. Investigating the production provenance of iron artifacts with multivariate methods. *Journal of Archaeological Science* 39, 2280–2293.
- Chic, G., 2005. El comercio de la Bética altoimperial. *Habis* 36, 313–332.
- 305 Crema, E.R., Kerig, T., Shennan, S., 2014. Culture, space, and metapopulation: a simulation-based study for evaluating signals of blending and branching. *Journal of Archaeological Science* 43, 289–298.
- Díaz Trujillo, O., 1992. Excavación arqueológica de urgencia en el Cerro de Belén: Palma del Río, Córdoba, in: *Anuario Arqueológico de Andalucía*. Junta de Andalucía, pp. 121–129.
- 310 Diniz-Filho, J.A.F., Soares, T.N., Lima, J.S., Dobrovolski, R., Landeiro, V.L., Telles, M.P.d.C., Rangel, T.F., Bini, L.M., 2013. Mantel test in population genetics. *Genetics and Molecular Biology* 36, 475–485.
- Eerkens, J., Lipo, C., 2005. Cultural transmission, copying errors, and the generation of variation in material culture and the archaeological record. *Journal of Anthropological Archaeology* 24, 316–334.
- 315 Eerkens, J., Lipo, C., 2007. Cultural Transmission Theory and the Archaeological Record: Providing Context to Understand Variation and Temporal Changes in Material Culture. *Journal of Archaeological Research* 15, 239–274.
- 320 Fernández, P.S., Muñoz, J.T., Vargas, E.G., de la Vega, S.G.D., 2001. Excavación arqueológica de urgencia en el alfar romano de las Delicias (Écija, Sevilla) 1997., in: *Anuario arqueológico de Andalucía* 1997. Junta de Andalucía, pp. 562–575.

- Funari, P., 2005. The Economic history of Roman Britain: olive oil contribution  
325 to the debate. *História e economia* 1, 29–46.
- Gandon, E., Roux, V., Coyle, T., 2014. Copying errors of potters from three cultures: predictable directions for a so-called random phenomenon. *Journal of Anthropological Archaeology* 33, 99–107.
- García Vargas, E., 2000. Ánforas romanas producidas en Hispalis: primeras  
330 evidencias arqueológicas. *Habis* 31, 235–260.
- García Vargas, E., 2010. Formal Romanisation and the Atlantic Projection of Amphorae from the Guadalquivir Valley, in: The Western Roman Atlantic Façade: A study of the economy and trade in the Mar Exterior from the Republic to the Principate. archaeopress ed.. Oxford, England. number 2162  
335 in BAR International Series, pp. 55–66.
- García Vargas, E., Morena, J.A., forthcoming. La excavación del alfar de ánforas Dr. 20 de Villaseca (Córdoba). Unpublished.
- Hart, J.P., 2012. The effects of geographical distances on pottery assemblage similarities: a case study from Northern Iroquoia. *Journal of Archaeological Science* 39, 128–134.  
340
- Hosfield, R., 2009. Modes of transmission and material culture patterns in craft skills, in: Pattern and Process in Cultural Evolution. Origins of Human Behavior and Culture, 2. University of California Press, pp. 45–60.
- Isaksen, L., 2006. Network analysis of transport vectors in Roman Baetica, in:  
345 Digital discovery: exploring new frontiers in human heritage. Proceedings of the 34th CAA Conference, Fargo, pp. 76–87.
- Jarvis, A., Reuter, H., Nelson, A., Guevara, E., 2008. Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from <http://srtm.csi.cgiar.org>.
- Jolliffe, I., 2002. Principal component analysis. Wiley Online Library.  
350

- Li, X.J., Bevan, A., Martinón-Torres, M., Rehren, T., Cao, W., Xia, Y., Zhao, K., 2014. Crossbows and imperial craft organisation: the bronze triggers of China's Terracotta Army. *Antiquity* 88, 126–140.
- Mantel, N., 1967. The detection of disease clustering and a generalized regression approach. *Cancer Research* 27, 209–220.
- Martin-Kilcher, S., 1987. Die römischen Amphoren aus Augst und Kaiser-augst. Ein Beitrag zur römischen Handels- und Kulturgeschichte, 1. Die südspanischen Öl'amphoren (Gruppe 1). volume 7/1. *Forschungen in Augst*.
- Mattingly, D.J., 1988. Oil for export? A comparison of Libyan, Spanish and Tunisian olive oil production in the Roman Empire. *Journal of Roman Archaeology* 1, 33–56.
- Mauné, S., García Vargas, E., Bourgeon, O., Corbeel, S., Carrato, C., García Dils, S., Bigot, F., Vázquez Paz, J., 2014. L'atelier d'amphores à huile Dr. 20 de Las Delicias à Écija (prov. de Séville, Espagne), in: SFECAG, Actes du Congrès de Chartres, pp. 419–444.
- Mesoudi, A., 2015. Cultural Evolution: A Review of Theory, Findings and Controversies. *Evolutionary Biology* 43, 481–497. URL: <http://link.springer.com/10.1007/s11692-015-9320-0>. doi:10.1007/s11692-015-9320-0.
- Neff, H., 1992. Ceramics and evolution. *Archaeological Method and Theory* 4, 141–193.
- Neiman, F.D., 1995. Stylistic variation in evolutionary perspective: inferences from decorative diversity and interassemblage distance in Illinois Woodland ceramic assemblages. *American Antiquity* 60, 7–36.
- Oksanen, J., Kindt, R., Legendre, P., O'Hara, B., Stevens, M.H.H., Oksanen, M.J., Suggs, M., 2007. The vegan package. *Community ecology package* 10, 631–637.

- Remesal, J., 1977. La economía oleícola bética: nuevas formas de análisis. *Archivo Español de Arqueología* 50, 87–144.
- Remesal, J., 1986. La amnona militaris y la exportación de aceite bético a  
380 Germania. Editorial Complutense.
- Remesal, J., 1998. Baetican olive oil and the Roman economy. *Journal of Roman Archaeology - Suppl. series* 29, 183–200.
- Remesal, J., 2004. Las ánforas Dressel 20 y su sistema epigráfico. J. Remesal Rodríguez (ed.), *Epigrafía anfórica. Proyecto Amphorae, Instrumenta* 17,  
385 127–148.
- Richerson, P.J., Boyd, R., 2005. Not by genes alone. How culture transformed Human Evolution. Chicago: University of Chicago Press.
- Ripley, B., Venables, B., Bates, D.M., Hornik, K., Gebhardt, A., Firth, D., Ripley, M.B., 2013. Package ‘mass’. *Cran R* .
- 390 Roux, V., 2015. Standardization of ceramic assemblages: Transmission mechanisms and diffusion of morpho-functional traits across social boundaries. *Journal of Anthropological Archaeology* 40, 1–9.
- Rubio-Campillo, X., Coto-Sarmiento, M., Remesal, J., 2017. Bayesian analysis and free market trade within the Roman Empire. *Antiquity* 91, 1241–1252.
- Schillinger, K., Mesoudi, A., Lycett, S.J., 2016a. Copying error, evolution, and phylogenetic signal in artifactual traditions: An experimental approach using “model artifacts”. *Journal of Archaeological Science* 70, 23–34.
- 395 Schillinger, K., Mesoudi, A., Lycett, S.J., 2016b. Differences in Manufacturing Traditions and Assemblage-Level Patterns: the Origins of Cultural Differences in Archaeological Data. *Journal of Archaeological Method and Theory* 24, 640–658. doi:10.1007/s10816-016-9280-4.
- Shennan, S., 2002. Genes, memes, and human history: Darwinian archaeology and cultural evolution.

- Shennan, S., 2008a. Evolution in Archaeology. *Annual Review of Anthropology* 37, 75–91. URL: <http://www.annualreviews.org/doi/abs/10.1146/annurev.anthro.37.081407.085153>, doi:10.1146/annurev.anthro.37.081407.085153.
- 405 Shennan, S., 2008b. Quantifying archaeology. Edinburgh University Press.
- Shennan, S.J., Crema, E.R., Kerig, T., 2015. Isolation-by-distance, homophily,  
410 and “core” vs. “package” cultural evolution models in Neolithic Europe. *Evolution and Human Behavior* 36, 103–109.
- Shennan, S.J., Wilkinson, J.R., 2001. Ceramic Style Change and Neutral Evolution: A Case Study from Neolithic Europe. *American Antiquity* 66, 577–593.  
URL: <http://www.jstor.org/stable/2694174>.
- 415 Steele, J., Glatz, C., Kandler, A., 2010. Ceramic diversity, random copying, and tests for selectivity in ceramic production. *Journal of Archaeological Science* 30, 1–11.
- Thorpe, O.W., Warren, S.E., Nandris, J., 1984. The distribution and provenance of archaeological obsidian in Central and Eastern Europe. *Journal of Archaeological Science* 11, 183–212.
- 420 Van Strien, M.J., Holderegger, R., Van Heck, H.J., 2015. Isolation-by-distance in landscapes: considerations for landscape genetics. *Heredity* 114, 27–37.
- Wickham, H., Chang, W., others, 2016. ggplot2: create elegant data visualisations using the grammar of graphics. R package version 2.