



Reconstructing Mesolithic social networks on the Iberian Peninsula using ornaments

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Abstract

Archaeologists have been reconstructing interactions amongst hunter-gatherer populations for a long time. These exchanges are materialised in the movements of raw materials and symbolic objects which are found far from their original sources. Social network, i.e. the structure constituted by these interactions, is a well-established concept in archaeology that is used to address the connectivity of hunter-gatherer populations. The heuristic potential of formal network analysis, however, has been scarcely exploited in prehistoric hunter-gatherer archaeology. Here, social network analysis is used to analyse the interactions amongst hunter-gatherers on the Iberian Peninsula in the Early and Late Mesolithic (10,200 to 7600 cal BP). We used ornaments to explore social interaction and constructed one network per phase of the Iberian Mesolithic. We applied a three-steps analysis: First, we characterised the overall structure of the networks. Second, we performed centrality analysis to uncover the most relevant nodes. Finally, we conducted an exploratory analysis of the networks' spatial characteristics. No significant differences were found between the overall network topology of the Early and Late Mesolithic. This suggests that the interaction patterns amongst human groups did not change significantly at a peninsular scale. Moreover, the spatial analysis showed that most interactions between human groups took place over distances under 300 km, but that specific ornament types like *Columbella rustica* were distributed over more extensive distances. Our findings suggest that Iberian Mesolithic social networks were maintained through a period of environmental, demographic and cultural transformation and that interactions took place at different scales of social integration.

Keywords Mesolithic · Social network analysis · Iberian Peninsula · Shell ornaments

Introduction

Archaeologists have been studying the interactions amongst hunter-gatherer populations for a long time. Such exchanges are embodied in the movement of raw materials and symbolic objects that have been found far away from their original sources (Wobst 1974, 1976; Gamble 1998). A social network, i.e. the structure that emerges from those interactions, is a well-established concept in archaeology which allows to estimate connectivity amongst hunter-gatherer populations. The heuristic potential of formal network analysis, however, has hitherto been scarcely exploited in prehistoric hunter-gatherer archaeology. This paper presents a first approach to the reconstruction and analysis of hunter-gatherer socio-spatial patterns of interaction between the Early Mesolithic (ca. 10,200–8600 cal BP) and Late Mesolithic (8600–7600 cal BP) as established by various periodisation models (Montes et al. 2006; Martí Oliver 2009; Carvalho 2010; Aura et al.

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2011; Bicho and Haws 2012; Soto et al. 2015; Straus 2018). Table S1 in the Supplementary information provides a detailed chronology on the Iberian Peninsula. Hunter-gatherer (hereafter, H-G) social networks refer to the structure resulting from inter- and intra-regional interactions within and amongst H-G regional groups. The function of these interactions, the resources used to maintain them, and their spatial scale all depend on the level of social integration in which they occur (Wobst 1974; Gamble 1998; Whallon 2006). Social interactions were embedded in the activities of all H-G groups, and as such, material culture patterns in the archaeological record are a direct result of these interactions (Coward 2010).

The number of studies on past population social networks has risen sharply in recent years (Peeples 2019), as is visible in the publication of specialised books (Knappett 2011), edited volumes (Knappett 2013; Brughmans et al. 2016), or journal special issues (Collar et al. 2015; Evans and Felder 2016). The potential of this methodological approach is illustrated by the wide range of case studies, topics and research questions to which network analysis has recently been applied: the detection of communities at Çatalhöyük (Mazzucato 2019); the emergence of inequality in Maya settlements (Thompson et al. 2021); the structure of Clovis social networks (Buchanan et al. 2019); the rates of adoption and diffusion of innovation (Kandler and Caccioli 2016) or social signalling at regional scale (Hart et al. 2017; Birch and Hart 2018).

Nevertheless, the formal analysis of hunter-gatherer social networks is still very limited (Gjesfeld 2015; Romano et al. 2020). Only two detailed studies in European Prehistory have been conducted. Riede (2014) modelled long-distance interactions using exotic non-utilitarian objects as proxies, such as ornament shells, amber and zoomorphic figurines made with known raw material sources. He showed that social network breakdowns could explain the reduction in technological complexity observed in southern Scandinavia after the Laacher See eruption (ca. 13,000 years ago). The second case study focused on the reconstruction of Lower Magdalenian social networks in the North of the Iberian Peninsula. Similarities of figurative portable art representations were used as a proxy for social interaction (Gravel-Miguel 2016). Here, the primary goal was to demonstrate that archaeological social networks are better understood when they are interpreted in relation to their geographical and environmental contexts.

The challenge facing researchers who wish to study hunter-gatherer social networks is that social interactions are not directly preserved in the archaeological record: we thus have to rely on different proxies to approach them. Based on previous ethnographic and archaeological research, we decided to use ornaments as proxies to reconstruct social networks from evidences of shared cultural practises. In

ethnographic studies on hunter-gatherer groups, ornaments express group affiliation, personal identity and status; they form a key part of the exchange systems between different groups (Wiessner 1984). In the archaeological record, ornaments have been used as a proxy to reconstruct regional and even linguistic groups on the basis of social identity arising from shared cultural practices (Newell et al. 1990).

The study of personal ornaments to reconstruct the social landscape of prehistoric populations is a well established approach in palaeolithic archaeology. The geographical reach of a certain group can be approximately delineated by the geographical distribution of a certain type of ornament, or a collection of ornaments, over specific chronological periods, has been used to delineate the geographical reach of these groups. This approach has been applied by Vanhaeren and d'Errico (2006) to identify ethnolinguistic groups in Aurignacian Europe. Similarity between the ornament assemblages has also been interpreted as suggesting close interaction/cultural bonds between the symbolic spheres of the Levant and Europe during the same period (Tejero et al. 2021b) and then again between the Southern and Northern Caucasus (Tejero et al. 2021a) as previously observed through techno-typological similarities in their lithic-tool assemblages. Likewise, in the Cantabrian region of the Iberian Peninsula, the use of similar shell beads between the ornament assemblages of coastal and inland sites has been interpreted as an indicator of shared cultural practices between communities practicing different economical strategies (Rigaud and Gutiérrez-Zugasti 2016)

Ornaments and other exotic raw materials are also considered a proxy for interaction between distant groups. Concretely, when they are found far away from their raw material source, they are interpreted as a proxy for transport and exchange, associated with the establishment and maintenance of social networks (Newell et al. 1990; Whallon 2006). The transport of marine raw materials and shell beads has been documented in several instances. It is the case of the already cited work by Rigaud and Gutiérrez-Zugasti (2016). However, the most notable example of symbolic material transport is *Columbela rustica* during the Mesolithic. This case, which has been extensively studied by Álvarez Fernández (2008a), at the European and peninsular scale, and others like Boric and Cristiani (2016) in the Balkans and Italy, documented the transport of this gastropod from the Mediterranean shore to Europe's inland over distances greater than 300 km all. The works reviewed above highlight the importance of studying the patterns of distribution of ornaments to approximate to the social geography and networks of past populations.

Here, we focus on reconstructing and comparing social networks in the Early and Late Mesolithic on the Iberian Peninsula. This was a period of very significant transformations at the climatic, environmental, demographic

and technological levels. Chronologically, it unfolded (ca. 10,200–7600 cal BP) over the whole Early Holocene Boreal and the onset of the Middle Holocene Atlantic chronozones. These latter periods are characterised by a global trend of stabilisation under warmer and wetter climatic conditions (Cacho et al. 2001), interrupted by several cooling events, the most notable being the 8.2 kya climatic event (López-Sáez et al. 2007). These climatic changes had a transformative effect on the environment with a sea level rise (Peltier 2002) and the expansion of deciduous and thermophilous forests (Carrión et al. 2010; Gomes et al. 2020). With the onset of the Mesolithic came a shift in subsistence strategies: hunted species diversified and the exploitation of marine resources intensified (Aura et al. 2009; Alday and Soto 2017). From a demographic perspective, according to a logistic model of population growth (Fernández-López de Pablo et al. 2019), the period under study was characterised on the Iberian Peninsula by increasing population levels, subject to different subregional variation patterns. One of such subregional patterns, the Atlantic region of central and southern Portugal, has been recently described (McLaughlin et al. 2021): environmental carrying capacity shifts in estuarine areas were found to be closely linked to an increase in relative population size and settlement nucleation during the Late Mesolithic.

Culturally, the Iberian Peninsula Mesolithic is divided into two major cultural phases corresponding to two different technocomplexes. The first, the Early Mesolithic, also called the Notched and Denticulated Mesolithic (ca. 10,200–8600 cal BP), is technologically characterised by expeditious flake debitage strategies used to produce assemblages dominated by notches, denticulates and scrapers, including macrolithic tools (Alday 2006). During the second phase, the Late Mesolithic or the Geometric Mesolithic (ca. 8600–7600 cal BP), debitage systems changed radically towards the production of blades and bladelets, as well as projectiles with geometric microliths, mainly trapezes and triangles, using the microburin technique (Utrilla and Montes 2009).

The application of SNA to this chrono-spatial context allows us to quantitatively assess whether all these demographic and cultural changes translated into significant modification of the Iberian socio-spatial structure. In this article, we contribute to this study by analysing shared cultural practices represented in the ornaments' archaeological record.

Data and methods

Data collection

A georeferenced database of ornament assemblages from the Iberian Peninsula ascribed to either to the Early or Late Mesolithic was elaborated using specialised publications

and grey literature. This database is part of a much more extensive relational database drawn up for the ERC project Paleodem. Table 1 summarises the information recorded in the database (see Supplementary Tables 2 and 3 for details). The original database contains a total of 106 assemblages from 62 archaeological sites. Considering ornament assemblages by chrono-cultural period, we have a higher number of Late Mesolithic sites compared to Early Mesolithic sites.

Initially, each of the contexts was assigned to one of the two phases of the Mesolithic based on the chrono-cultural attribution of their material assemblage as it was specified by the researchers originally studying the materials. In a second step, a data quality control protocol was set up. Two criteria were established to rank archaeological assemblages' chrono-cultural reliability: (i) the integrity of both, the stratigraphic context and the association between radiocarbon dates and ornaments assemblages and (ii) the accuracy of the radiocarbon measurements considering the radiocarbon method (conventional or AMS), the laboratory error measurements and the inbuilt age of the samples. According to these criteria, four reliability levels were assigned (see Supplementary Materials, Tables S5 and S6):

- Level 1: Refers to the most reliable ornament assemblages that can be associated to undisturbed stratigraphic context with well-characterised Mesolithic chrono-cultural attribution, along with accurate radiocarbon dates.
- Level 2: Designates contexts with a clear cultural attribution but not directly associated with absolute radiocarbon dates. These contexts can be framed using the radiocarbon dates from stratigraphically close contexts.
- Level 3: This code was assigned to ornament assemblages from contexts with a reliable cultural attribution that cannot be associated to any radiocarbon date nor framed with any stratigraphically close contexts. Also, those contexts with inconsistent radiocarbon dates were coded with this value.
- Level 4: Those contexts with unreliable cultural attribution and no radiocarbon dates available were labelled with this code. The context assigned to this level was not included in any analytical step.

Table 1 Summary of the information contained in the database

	Sites/assemblages (raw data)	Sites/assemblages (curated/aggregated)
Early Mesolithic	26/39	25/25
Late Mesolithic	36/67	35/35
Total	62/106	60/60

Once the archaeological contexts of ornament assemblages' provenance were ranked, we unified contexts of the same site that were ascribed to the same Mesolithic phase, either the Early or Late Mesolithic, i.e. absolute number of ornaments from two or more levels of the same chronocultural period were computed together.

Since our objective was to account for the differences between the two units of the Iberian Mesolithic, we aggregated the levels from the same site which chronologically fell within the same unit. This is a common practice in the analysis of archaeological networks (Peeples et al. 2016). As a result, the Early Mesolithic group contained 25 assemblages, and the Late Mesolithic contained 35 (the geographical distribution is illustrated in Fig. 1). Worthy of note, these numbers preserve the original archaeological information ratio, in which the Late Mesolithic presents more sites and assemblages than the Early Mesolithic (Table 1). Next, we transformed the raw data to verify the impact of sample biases on ornament assemblages. We generated two file formats: (i) relative frequencies by ornament type and (ii) presence or absence of ornament type per assemblage (Supplementary materials Tables S2 and S3).

Similarity matrices and network construction

The above-collected data were used to construct cultural similarity matrices of ornament assemblages—a step that is widely applied in the construction of archaeological networks (Peeples et al. 2016). To this end, we used a similarity measure based on absence-presence (i.e. Jaccard index), instead of the (also common in archaeological networks' literature) Brainerd-Robinson frequency-based similarity

index. This decision was based on a two-fold reason. First, the amount of ornaments recovered from a particular archaeological site might be strongly conditioned by the specific site function and excavation techniques used (Rigaud et al. 2018). This fact discourages the application of frequency-based similarity measures to multiple sites. Secondly, by construction, Jaccard's coefficient has been reported to be more sensitive to the presence of the less widespread types in the sample, whilst Brainerd-Robinson tends to highlight the most common ones (Prignano et al. 2017). Given the extensive presence of *Columbella rustica* in the Iberian Mesolithic record (Álvarez Fernández 2008a), the Brainerd-Robinson coefficient was not appropriate for our dataset. Jaccard indices were calculated using Past statistical software (Hammer et al. 2001).

Similarity matrices were transformed into networks to prepare them for social network analysis (SNA). In this approach, social actors and their interactions are mathematically quantified and graphically represented as nodes and links. SNA offers a rigorous conceptual framework to describe the structure of networks together with methods to analyse and interpret them (Mills 2017). Specifically, we constructed a similarity network for each period of interest on the assumption that ornament assemblage similarities reflect shared cultural practises and, therefore, some level of social interaction. In our networks, nodes represent ornament assemblages and links represent a similarity amongst them. These links are undirected since similarity is a non-directed phenomenon. Their weight (i.e. the value quantifying their importance) corresponds to the similarity index. When constructing archaeological networks based on cultural similarity, it is quite common to erase links whose

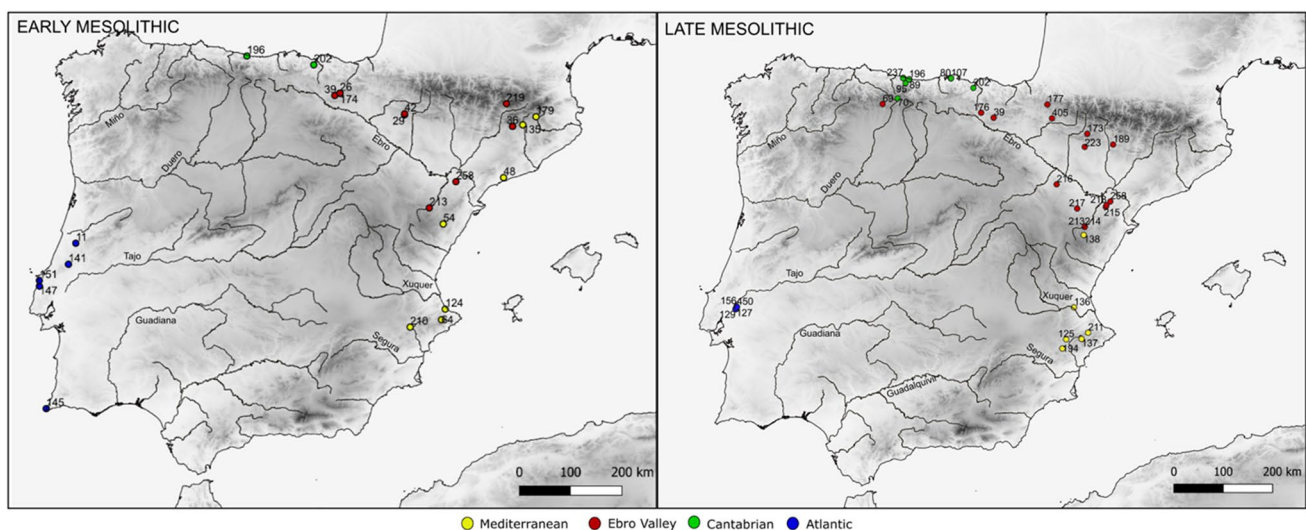


Fig. 1 Distribution of sites with ornament assemblages used to reconstruct the archaeological networks. Sites are identified by their ID number and the region they belong to. The correspondence between

IDs and names is detailed in the Supplementary materials Tables S2 and S3. The figure was created using QGIS 3.2.3 (QGIS.org 2021)

similarity value does not reach a minimum threshold. This is an easy and intuitive way to reduce the overall density of the resulting network (whilst keeping ‘important enough’ links) and, hence, have a clearer perspective of the general structure of the network under study. In our case, the link density of both networks kept rather low and the general structure was already visible (see the ‘General structure characteristics’ subsection within the ‘Results’ section). Consequently, we decided not to impose any threshold to network links between nodes. We used igraph R package (Csardi 2006) to construct and analyse the networks.

As part of the process of network construction, we needed to assess the impact of archaeological data reliability on the network structures. To this end, we constructed and compared several networks, capturing different levels of reliability. First, we constructed one network for each period (the Early Mesolithic and Late Mesolithic) using archaeological contexts that reached the chrono-cultural reliability levels 1 and 2. A second pair of networks was then elaborated by adding the assemblages from level 3 contexts. Assemblages classified as level 4 were not used in any analytical step due to their significant unreliability. Next, we calculated the overall structure of our four networks using density, average degree, weighted average degree, clustering coefficient and average path length metrics (see S.Table 3 and S.Text 2 in the Supplementary materials for further details). Following a careful comparison of the global metrics of the networks for each period, we concluded that the addition of less reliable information (i.e. level 3) did not alter the overall network topology but did contribute to network completeness. Consequently, we decided that the final networks to be analysed in depth would include all assemblages up to a chrono-cultural reliability level 3, resulting in an Early Mesolithic network of 25 assemblages and a Late Mesolithic of 35 assemblages.

Network analysis

Three complementary approaches were used to analyse the networks. All network metrics involved in these three analytical approaches are defined in Table 2. First, we characterised the general structure of both networks using density, average degree, weighted average degree, average clustering coefficient and average path length. Second, a node-level analysis was performed to uncover the most relevant nodes in each network (i.e. the most connected nodes or those with the strongest connections). Finally, we evaluated the networks using spatial characteristics. A summary of the methods applied can be found in Table 2.

Specifically, we performed a series of analysis for the spatial characterisation. First, we investigated whether nodes ascribed to the same geographical unit showed connection preference. To do so, we calculated the assortativity coefficient for both networks (Newman 2002). Second,

we explored the differences regarding the geographical distances covered by the networks’ links for each period. Figure 5 presents the frequency of links in relation to the distance covered by the links. Although the links reflect a shared cultural practice rather than direct contacts between hunter-gatherer groups, we chose to take the topography into account and adopted a human perspective regarding the distance measurements. We produced a matrix of geodetic distances geodetic, i.e. the shortest distance between each pair of nodes connected through a link, using the XY To Line geoprocessing tool from ArcGIS (ESRI, 2017) considering a 3 arc Digital Elevation Model of the Iberian Peninsula (Instituto Geográfico Nacional, ETRS89, UTM zone 30). Lastly, we examined the relation between the weight of the links and their covered distance using Spearman’s correlation test.

Results

Data variability and frequency distribution

We observed geographical and chronological patterns of the taxa used for the elaboration of ornaments. Assemblages were ascribed to one of the five geographical units (i.e. Cantabria, Atlantic, Mediterranean, Interior and Ebro Valley) which are traditionally used by Iberian prehistorians as units of analysis (e.g. Utrilla and Montes 2009; Álvarez-Fernández 2006). In Southern Portuguese sites, the most common taxon was *Theodoxus fluviatilis*, a freshwater snail widely distributed from Europe to Central Asia. In the Cantabrian sites, the most numerous taxa were *Trivia* sp., followed by *Littorina obtusata* of Atlantic origin. The Mediterranean record is dominated by *Columbella rustica*, an exclusively Mediterranean species. Finally, in the Ebro Valley, we found a mixture of the ornaments documented in the Cantabrian and Mediterranean geographical units.

This representation pattern coincides with the observations made by Álvarez-Fernández (2010, 2011) regarding the Cantabrian and Ebro Valley. Chronologically, we observe that the same taxa were used to make ornaments during both periods. However, we could observe changes in the relative frequencies of some taxa (Fig. 2). For example, although *Columbella rustica* dominates in ornament assemblages in both phases, it is more frequent in the Late Mesolithic. The same pattern can be observed with respect to *Trivia* sp. Conversely, *Nassarius reticulata* is more frequent in the Early Mesolithic than in the Late Mesolithic. Network analysis allowed us to use such variability to explore cultural patterns of interaction and potential changes throughout the Iberian Mesolithic.

Table 2 Definition of network properties and their respective meanings in our case study

Level	Network metrics	Definition	Meaning in the study case	Reference
Network level	Density	Defined as the ratio of the number of links and the number of possible links.	The general level of similarity between the different assemblages in the network. Values range from 0 to 1. High values imply that there is a high percentage of nodes that share some degree of similarity.	Scott (2017)
	Average clustering coefficient	The number of closed triads out of the total in the network, where a triad is set of three nodes with two (open triplet) or three (closed triplet) undirected links between them.	This is a general measure of cohesion. It is based on the existence of triads sharing a similar ornament assemblage.	Scott (2017)
	Average path length	It is defined as the average number of steps of the shortest path for all possible pairs of nodes in the network.	It measures 'how far' nodes are from each other and can be used to investigate the efficiency of information transmission within the network for example.	West 1996
	Assortativity coefficient	It measures the level of homophily of the network. It is based on some node labelling or values assigned to nodes. A high coefficient means that connected nodes tend to have the same label or similar assigned values.	This metric will tell us if the composition of an assemblage is similar to any other assemblage within the same geographical unit. It can be interpreted as regional traditions or common practice amongst groups.	Newman (2002)
Centrality	Betweenness centrality	This metric measures the number of times a node lies on the shortest path between other nodes.	Identifies the nodes that act as bridges between nodes in the network. High values in our case study would therefore correspond to the assemblages in the network that present unusual combinations of ornament types, making them the bridge between assemblages that have nothing in common.	Freeman (1979)
	Degree	The degree of a node is defined as the number of links connected to a specific node.	Determines which assemblages have more types in common with the nodes in the network. A similarity between nodes can be due to very diverse assemblages or assemblages only containing a type widely present across the nodes.	Freeman (1979)
	Weighted degree	Like the degree, this metric is based on the number of links to a node but pondered by the weights of the links.	Identifies the nodes which have a lot in common with a high number of other assemblages in the network.	Freeman (1979)

Fig. 2 Relative presence of ornament types in each Mesolithic phase on the Iberian Peninsula. The figure was created using R 4.0.5 (R Core Team 2013)

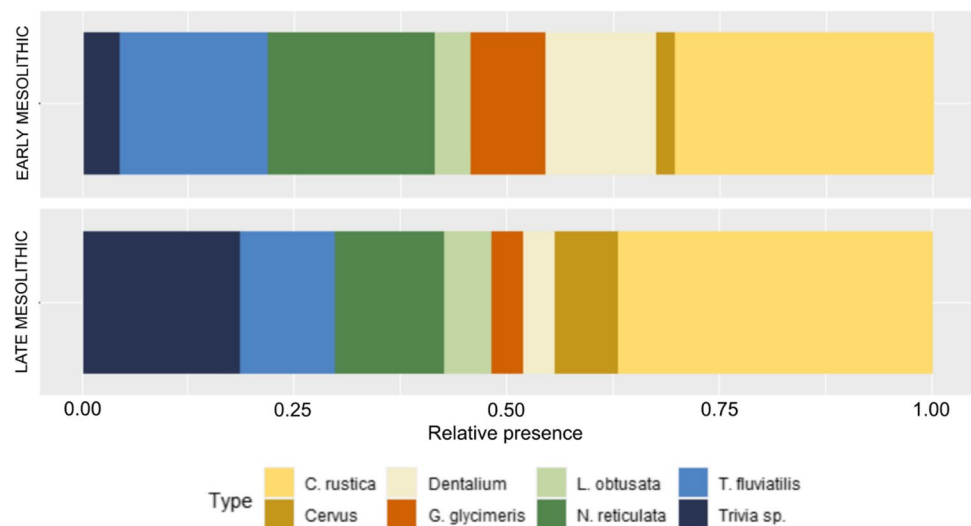


Table 3 Characterisation of the overall network in the Early and Late Mesolithic

Network metric	Early Mesolithic	Late Mesolithic
Num. Nodes	25	35
Num. Links	129	268
Density	0.43	0.45
Average clustering coefficient	0.77	0.80
Average path length	1.69	1.57

General structure characteristics

The results of the general structure analysis for the two periods are presented in Table 3. Both the Early and Late Mesolithic networks presented density values below 0.5 (i.e. less than half the connections they could have had). One can observe only a slight difference between the average clustering coefficient values and average path length between both networks. A more relevant aspect, however, is the relationship between both metrics. Both networks yielded high-average clustering coefficient values and low-average path length ones. These results suggest that our two networks present highly similar structures. In other words, no significant changes could be observed between the Early Mesolithic and the Late Mesolithic networks. This conclusion fits with the visual inspection of Fig. 3. In both networks, we basically observe two densely connected clusters of nodes, cross-linked by rather weak connections (in terms of similarity).

Centrality metrics

Each node's specific centrality values are listed in the Supplementary material (Tables S8 and S9). Here, we show their distribution on the Iberian Peninsula, and we refer to nodes

with the highest values (i.e. the quarter of the nodes with the highest values for each specific metric).

The highest degree nodes in the Early Mesolithic (Fig. 4a) represent the assemblages from sites located in Alicante, Northern Catalonia and the upper Ebro Valley, including the sites of Santa Maira, El Collado and Atxoste. In the Late Mesolithic network, the nodes with the highest values in this metric are concentrated within the Mediterranean geographical unit and the lower and upper Ebro River basin, three of which are Fuente Hoz, Aizpea and Pontet, amongst others. Conversely, the nodes with the lowest values are situated in Portugal and the western half of the Cantabrian region (Fig. 4d).

Interestingly, the nodes with the highest weighted degree in the Early Mesolithic network (Fig. 4b) are different from those with the highest value for this metric in the Late Mesolithic network (Fig. 4e). In the Early Mesolithic network, these nodes represent sites located in Alicante and the lower and upper Ebro valley, such as the sites of Angel 1, Arenal de la Virgen, Costalena or Kanpanoste Goikoa. In turn, in the Late Mesolithic (Fig. 4e), the nodes which yielded the highest weighted degree values are located in Alicante, the lower Ebro Valley and the western Pre-Pyrenees, including El Esplugón, Costalena or Casa Corona. All these nodes, in both networks, share a common feature: they represent assemblages composed of a single ornament type: *Columbella rustica*.

Lastly, the nodes presenting the highest betweenness in the Early Mesolithic (Fig. 4c) are located at four different ends of the peninsula: southern Portugal, the Cantabrian strip, the Lower Ebro Valley and Alicante. Some of these nodes represent the assemblages from Barranco das Quebradas, Santa Maira, Balma Margineda or Atxoste. In turn, in the Late Mesolithic network (Fig. 4f), nodes with the highest values in this metric are in the Cantabrian strip, the Upper

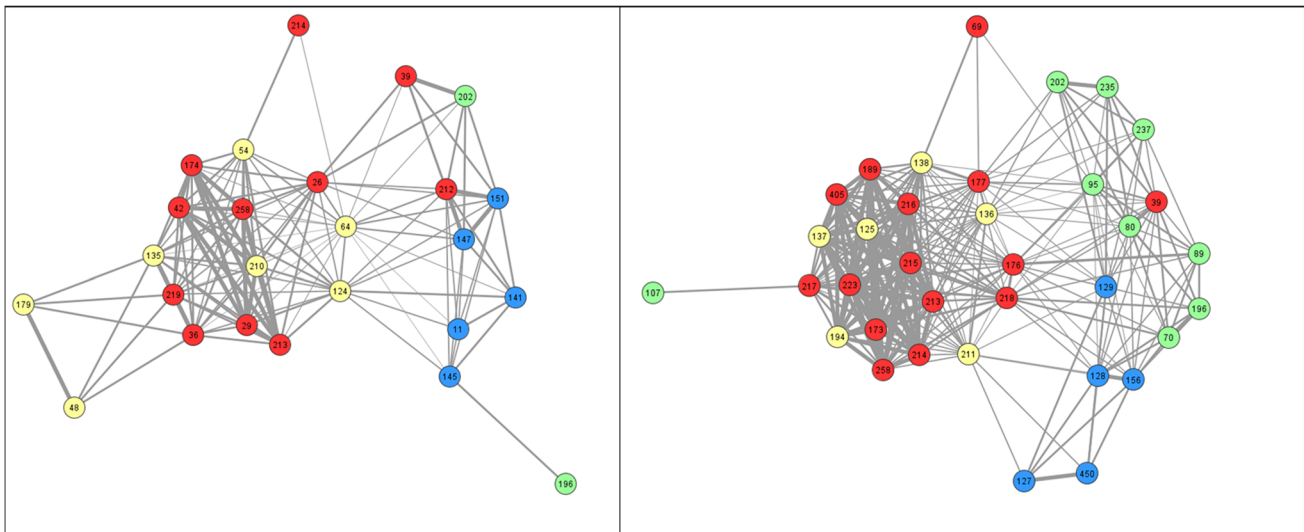


Fig. 3 Graphical representation of networks corresponding to the Early Mesolithic (left) and to the Late Mesolithic (right). Sites are identified by their ID number and the region they belong to (yellow: Mediterranean; green: Ebro Valley; red: Cantabrian; blue: Atlantic).

and Lower Ebro Valley and central Valencian Region. These nodes correspond to sites such as Benàmer, Los Baños, Aizpea and la Braña. Contrary to what we observed in the case of nodes with a high weighted degree, those with a high betweenness represent assemblages composed of various types of ornament.

Beyond the analysis of centrality metrics, the spatial perspective of Fig. 4 nicely complements the rather abstract network representation in Fig. 3. By comparing both figures, one can easily notice the interesting result that, despite the several changes on node position at the local scale, the general structure of the network keeps very similar. In order to further explore this spatial perspective, we conducted a number of analysis to assess the geographical characteristics of the obtained networks.

Spatial analysis

First, we applied assortativity measurement to quantitatively assess regionalisation and its change across the two snapshots in a simple way. Assortativity is a metric used in network analysis to measure to what extent links are preferentially established amongst nodes sharing some sort of attribute (more details can be found in Table 2). In our case, the attribute was the geographical unit nodes belonged to. Consequently, higher (more positive) values of assortativity corresponded to scenarios where links were more often established within the geographical unit. The value for the early Mesolithic network was 0.0836, whilst for the Late Mesolithic, it was 0.143. The values indicate that for both

periods, there is a weak tendency for any node to preferably connect with other nodes of the same geographical unit. The graphical representation was based on the Fruchterman-Reingold layout algorithm (Fruchterman and Reingold 1991) and created using Visone 2.20 (Brandes and Wagner 2004)

periods, there is a weak tendency for any node to preferably connect with other nodes of the same geographical unit.

We were particularly interested in the distances covered by the links of our networks. Figure 5 shows the frequency distributions of geographic distances covered by links in each network. In both cases, the number of links was found to decrease as the covered distances increased. This finding was quantitatively supported by the results of Spearman's correlation tests, showing a moderate negative correlation for both the Early Mesolithic ($Rho = -0.3304$, $p = 5.2442E-05$) and Late Mesolithic ($Rho = -0.29854$, $p = 1.461E-06$) networks. Moreover, both histograms presented a drop in link counts for distances greater than 300 km. In the Early Mesolithic network, links covering distances below 300 km accounted for 55.56% of the total, and in the Late Mesolithic network, the percentage rises to 66.93%. These results agree with the regionalisation observed above and provide a more precise view on its progress.

Histograms in Fig. 5 also allow us to assess the maximum range of the interactions according to the type of ornament. Specifically, we were interested in the distribution of ornaments made with Cantabrian or Mediterranean endemic species outside their areas of origin, and whose occurrence could be interpreted as the result of the interaction and exchange between distant groups (Newell et al. 1990; Whallon 2006; Riede 2014). The interactions between the Mediterranean and the rest of the Iberian Peninsula involving *Columbella rustica* (Fig. 5, in red) ranged from 100 to 500 km during the Early Mesolithic, and from 100 to 550 km during the Late Mesolithic. For their part, the interactions involving Cantabrian taxa (i.e. *Littorina obtusata*

and *Trivia* sp.) suggest a smaller range. More concretely, the maximum range of distribution of *Littorina* in the Late Mesolithic is a little over 170 km connecting the Cantabrian to the upper Ebro Valley. The maximum range of interaction involving *Trivia* would be almost 500 km, from Asturias to Zaragoza. This does not imply that a specific ornament travelled those distances during a single ‘interaction event’. Specifically, it means that within this range, interactions and exchanges took place in which these ornaments had a symbolic meaning. Lastly, the Spearman’s correlation test used to analyse the correlation between the weight of the links and the distance they covered showed a moderate negative correlation for both the Early Mesolithic ($p = -0.3304$, $p = 5.2442E-05$) and Late Mesolithic ($p = -0.29854$, $p = 1.461E-06$) networks. Finally, to further explore these spatial observations, we divided the links into three groups according to their weight (i.e. the similarity value provided by the Jaccard index): low weighted links (values up to 0.39), middle weight (from 0.4 to 0.69) and high weight (from 0.7 to 1). The distribution of the distances covered by the links in each group is illustrated in Fig. 6. The boxplots corresponding to the Early Mesolithic links show a pattern in line with our general expectations: links with a low weight cover greater distances than those with a high weight, which thus cover the shorter distances. Results corresponding to Late Mesolithic present a deviation from such expectations. Specifically, links presenting both medium and low similarity are shorter than their equivalent at the Early Mesolithic. Notice that this finding is compatible with the increase of regionalisation identified above.

Discussion

Evaluation of the method against the representativeness of the Iberian Mesolithic record: problems and corrective strategies

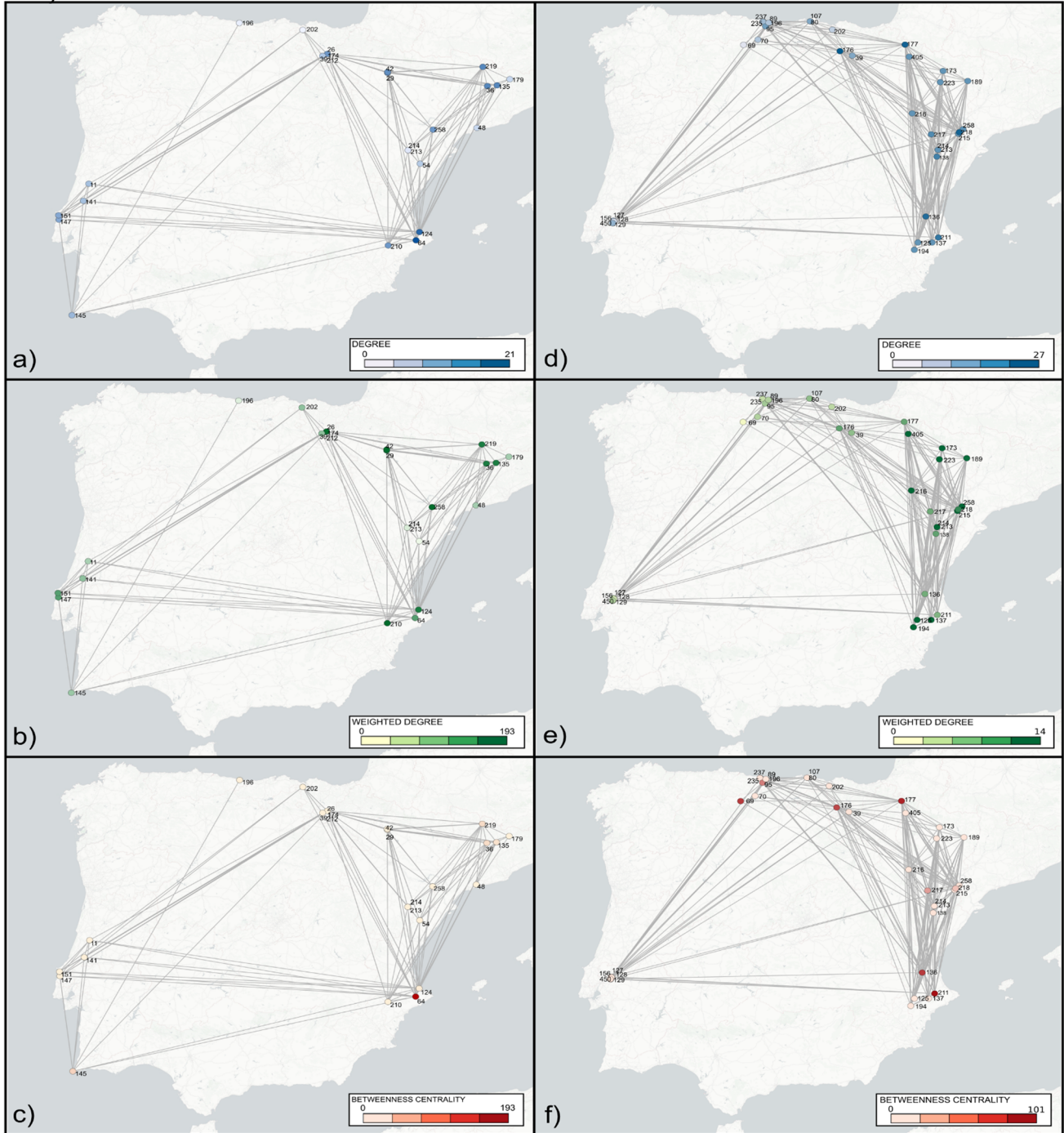
The present study aimed at characterising and comparing the patterns of interaction amongst human groups during both phases of the Iberian Mesolithic. Because the use of SNA is still incipient in prehistoric archaeology, it was necessary, first, to evaluate the potential and the limitations of this methodological approach to understand Mesolithic social networks. Recent studies have discussed the potential problems of applying SNA to the H-G archaeological record, including (i) the impact of taphonomic processes on the preservation of the material record—especially considering the sort of activity residues and the palimpsest nature of most archaeological deposits (Gravel-Miguel and Coward 2021)—(ii) the so-called fragmentation problem (Gjesfeld 2015)—concerning the representativeness of the

archaeological record regarding different types of sites and research biases; (iii) the multi-scalar nature of social network structures (Hamilton et al. 2007) and its translation into specific network boundaries and (iv) the difficulty of assessing contemporaneity amongst different archaeological contexts in the reconstructed networks (Gjesfeld 2015).

As regards point (i), issues of site taphonomy regarding the preservation of material culture are indeed ubiquitous in the archaeological record. Their impact in the present study, however, was minimised due to the extensive use of all the available information on ornament assemblages, including different site types (open-air, caves and rock shelters) from a period that has in fact been intensively investigated over the past two decades (Alday and Cava Almuzara 2006; Utrilla and Montes 2009). In terms of the data’s geographic representativeness (problem ii), the distribution maps of the analysed assemblages (Figs. 1 and 4) reflect an evident lack of ornament assemblages from Andalusia and the Iberian interior. In Andalusia, the long stratigraphic sequences of Nerja and Bajondillo caves, on the Malaga coast, and Cueva del Nacimiento, in Jaén, were the only sites to yield a very limited lithic industrial evidence of trapezes dated to the Late Mesolithic (Cortés Sánchez 2007; Aura Tortosa et al. 2009). No ornament assemblages, however, have been published for those sites. With respect to the Iberian interior (referring to the North and South Iberian Plateaux), the lack of ornament assemblages is more clearly associated with an almost total absence of Mesolithic sites. Over the past two decades, Iberian prehistorians have discussed whether this pattern of ‘Mesolithic emptiness’ reflects a reorganisation of the settlement distribution in favour of coastal regions, forced by a carrying capacity reduction due to the very dense development of thermophilus forests (Zilhão 2001; Fernández-López de Pablo and Gómez-Puche 2009), or, on the contrary, whether it results from chronological and research biases (Arias Cabal and Fano 2009). Whilst such a discussion is beyond the scope of this study, we believe that the archaeological patterns observed in the Iberian interior reflect a significantly lower and chronologically discontinuous settlement density during the Early Mesolithic and an absence of reliable Late Mesolithic sites. In this respect, it is worth noting that commercial archaeology operations have been taking place on major motorway and wind farm infrastructure sites for over three decades. They supposedly provide chronologically unbiased evidence. Yet the documentation of open-air Mesolithic sites, such as Parque Darwin in Madrid (Escobar Requena 2010), remains an exception compared to both older (Cacho et al. 2010) and more recent prehistoric periods (Balsera et al. 2015). Thus, whilst the influence of research intensity and site preservation bias might be different for each regional unit and, therefore, difficult to quantify, our results are in line with previous studies and interpretations at regional scales. The

Early Mesolithic 10200 - 8600 cal BP

Late Mesolithic 8600 - 7600 cal BP



methodological approach presented here allows the addition of new evidence, so the networks can be easily actualised and our conclusions re-evaluated.

Concerning the contemporaneity problem of the assemblages included in each network, we opted for chronological aggregation in two broads, but taxonomically relevant time slices of 1600 and 1100 years each. Such a chronological scale allows capturing the aggregated record resulting from persistent patterns of shared cultural practises within

the two major and successive Mesolithic taxonomic units derived from lithic typology. In addition, these chronological aggregation intervals are comparable to other SNAs recently applied to the Palaeolithic archaeological record, with 1000–3000-year ranges (Gravel-Miguel and Coward; Coward 2010; Rivero and Sauvet 2014).

Finally, regarding the problem of translating network boundaries into the geographic space (problem iii), in this case study, we decided to set the whole Iberian Peninsula

Fig. 4 Network layout representing nodes/assemblages located according to their site coordinates. The colour represents the degree of each node: the darkest the colour, the higher its value. Each node is identified by its ID; see Tables 1 and 2 for the ID's corresponding names. The existence of a link between two nodes indicates some degree of assemblage similarity. **a** Early Mesolithic network node colour according to their degree; **b** Early Mesolithic network node colour according to their weighted degree; **c** Early Mesolithic network node colour according to their betweenness centrality; **d** Late Mesolithic network node colour according to their degree; **e** Late Mesolithic network node colour according to their weighted degree; **f** Late Mesolithic network node colour according to their betweenness centrality. The figures were elaborated using Visone 2.20 (Brandes and Wagner 2004). 11.Buraca Grande; 26.Atxoste; 36.Legunova; 39.Mendandia; 42.Pena 14; 48.La Cativera; 54.Cova Fosca; 64.Santa Maira; 69.La Braña; 70.El Espertin; 80.La Garma; 89.El Mazo; 95.Los Canes; 107.Cueva del Mar; 124.El Collado; 125.Casa Corona; 127.Cabeço da Arruda; 128.Cabeço da Amoreira; 129.Moita do Sebastiao; 135.Font del Ros; 136.Cueva de la Cocina; 137.Falguera; 138.Mas Cremat; 141.Casal Papagaio; 145.Barranco das Quebradas; 147.Toledo; 151.Vale de Frade; 156.Vale Fonte Moça I; 173.El Esplugon; 174.Kanpanoste Goikoa; 176.Fuente Hoz; 177.Aizpea; 179.Sota Palou; 189.Forcas 2; 194.Lagrimal; 196.El Toral III; 202.Arenaza; 210.Arenal de la Virgen; 211.Benamer; 212.Kanpanoste; 213.Angel 1; 214.Angel 2; 215.Botiqueria dels Moros; 216.Cabezo de la Cruz; 217.Los Baños; 218.Pontet; 219.Balma Margineda; 223.Espantalobos; 235.Cueto de la Mina; 237.La Poza l'Egua; 258.Costalena; 405.Padre Areso; 450.Fonte de Moça II

as an analytical unit. The Iberian Peninsula has very well defined physical geographic boundaries and a *cul-de-sac* position at the southwestern tip of the Eurasian continent. In addition, from a biogeographic perspective, a major divide between the Euro-Siberian and Mediterranean regions can be recognised. In conjunction with geographic physical barriers, the divide allows us to explore some regional and subregional variation patterns in the archaeological record in terms of shared cultural practises.

Main findings and prospective research

Our study focused on ornament assemblage similarities to reconstruct socio-spatial patterns. Using this archaeological proxy, we assumed that ornament assemblage similarities would correspond to different social groups sharing similar cultural practices. The reconstructed social networks were thus analysed and compared following a three-fold investigation: general structural characteristics, nodes centrality and spatial distribution.

As far as social networks based on ornament assemblage similarity were concerned, our general structure analysis did not reveal significant differences between both networks at a global scale. One exception was the higher number of nodes and links for in the Late Mesolithic compared to the Early Mesolithic. This absence of difference suggests that populations interacted creating the same global patterns. This is a relevant finding considering the notable differences in lithic technology between the Early and Late Mesolithic. The

stability of personal ornament practices compared to other cultural markers (i.e. lithic industries) has been documented by previous research works in other Upper Palaeolithic and Mesolithic contexts in Eurasia (Vanhaeren and d'Errico 2006; Perlés 2013, 2019; Stiner 2014; Rigaud et al. 2015, 2018). From an Iberian Peninsula perspective, the continuity observed between the Early and Late Mesolithic ornament assemblage networks has also been recognised in other cultural domains such as settlement patterns, funerary practices based on individual burials (Gibaja et al. 2015) and from a circulation network perspective (Álvarez Fernández 2001).

The greater number of nodes and links observed during the Late Mesolithic may reflect an increase in population densities regarding the previous Early Mesolithic, a pattern that has been consistently documented at both Iberian and subregional scales (Barton et al. 2018; Fernández-López de Pablo et al. 2019; McLaughlin et al. 2021). Our study was able to capture this overall trend. It lacked, however, the chronological resolution required to address the socio-ecological impacts on social networks of the Early Holocene episodes of rapid climatic change, such as the 10.2, 9.2, the 8.6 and the 8.2 kya climatic events (González-Sampérez et al. 2009; Fernández-López de Pablo and Jochim 2010; Bicho and Haws 2012; García-Martínez de Lagrán et al. 2014).

The analysis of the spatial properties of both networks led to some interesting observations. First, the assortativity coefficient showed that interactions amongst nodes were slightly more frequent within each regional unit than between nodes in different regions. This metric might reflect the sort of nested social organisation in which these connectivity patterns were embedded: interactions amongst individuals, families and bands from the same regional group were more common than amongst those from different regions (Newell et al. 1990). This finding leaves room for future studies to focus on identifying regional groups using multi-proxy evidence and other network methods (e.g. modularity, community detection).

Second, the comparison of the frequency distributions of the link distances between the Early and Late Mesolithic networks reveals different spatial scales of social interaction. As presented earlier, in order to explore the spatial extension, i.e. the whole range of possible interactions within each network, we did not establish any threshold in terms of distances or similarity between ornament assemblages. The resulting frequency distributions of link distances that we observe in these unconstrained networks ranged from 0 up to a maximum of 900 km in the Early Mesolithic, and to 800 km in the Late Mesolithic. In both networks, the highest frequency distributions were clearly below 300 km with a progressive decrease for longer distances, i.e. in those ranging from 300 to 900 km. Visualisation of the frequency distribution densities of the *Columbella rustica* ornament

Fig. 5 Distribution of the number of links according to the distance they cover. Early (upper) and Late (lower) Mesolithic networks. The red colour indicates the links established between sites where *Columbella rustica* is present. The figure was created using R 4.0.5 (R Core Team 2013)

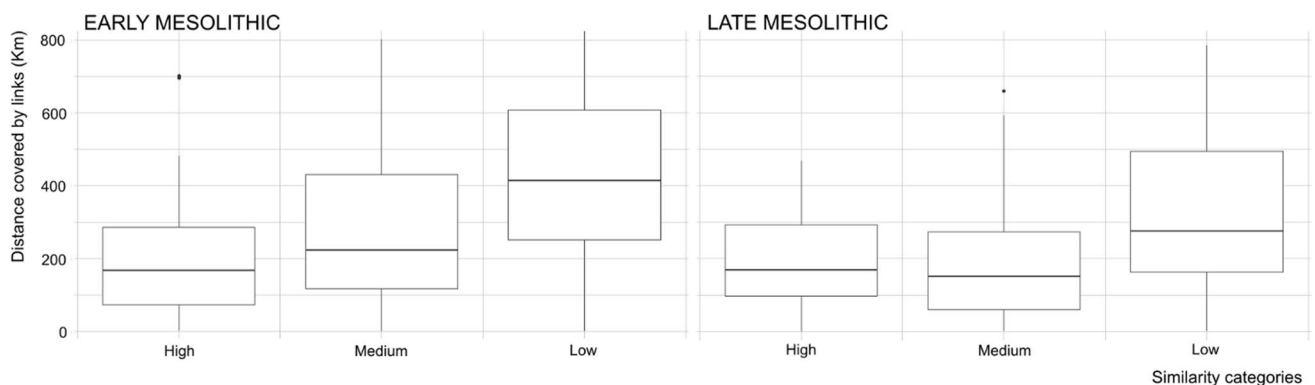
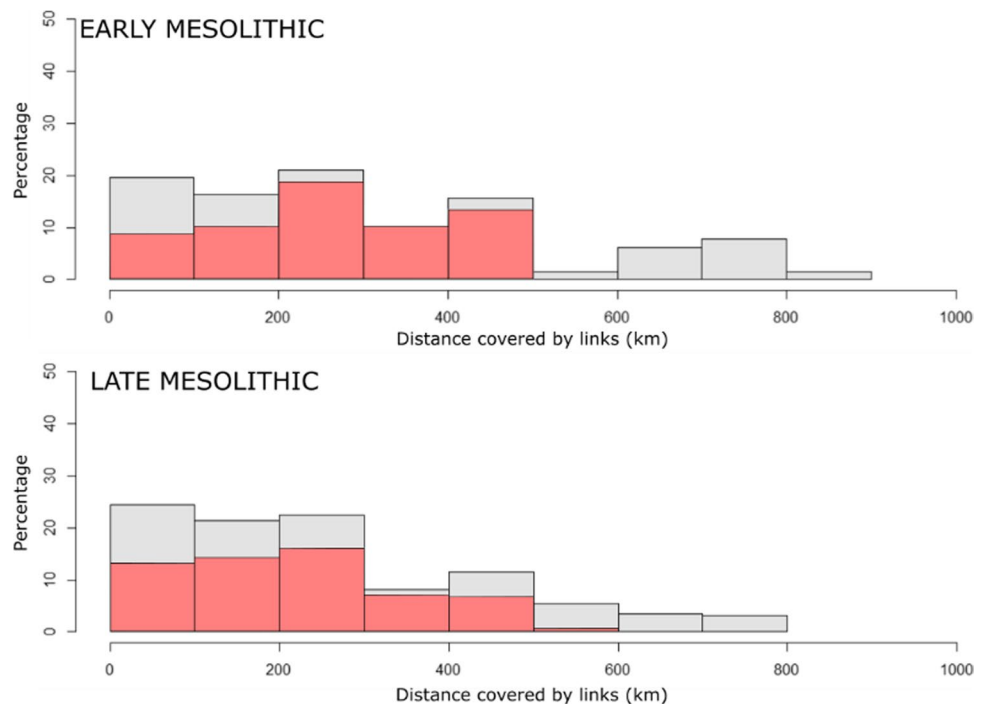


Fig. 6 Distribution of distances covered by links in each similarity group. The figure was created using R 4.0.5 (R Core Team 2013)

provided a more robust proxy for the spatial scales of social interactions. As seen in Fig. 5 (in red), the maximum distribution range was 0–500 km in the Early Mesolithic, and 0–600 km in the Late Mesolithic, with the highest distribution densities below 300 km. As from 300 km onwards, there is an evident decline in the distribution frequencies. In addition, the decline seems more pronounced in the Late Mesolithic network than in the Early Mesolithic network, where the density is more sustained. Such differences might reflect different scales of interaction within and amongst different social integration units.

Other Mesolithic case studies have used shell ornaments as a proxy for social interaction. They provide a frame of reference to interpret the results of our own analysis even though these works did not apply the same methodology.

In Southwestern Germany, according to the heuristic model proposed by Whallon (2006), decorative shells over distances ranging from 150 to 250 km became very common during the Early Mesolithic, reflecting interactions within the same maximal band. In contrast, shell ornaments found between 250 to 400 km would correspond to social interactions between adjacent maximal bands, and those over 600 km beyond adjacent maximal bands. In the Balkans, *Columbella rustica* shells have been documented over distances up to 100 km away from the shorelines during the Mesolithic (Boric and Cristiani 2016), and the same range is documented for the *Columbella rustica* in the Dolomites (Italy) (Álvarez Fernández 2008a). In the Iberian Peninsula, this marine gastropod is transported from the Mediterranean shores through the Ebro Valley until reaching

the South Western Pyrenees, specifically at the site of Berroberria (Álvarez Fernández 2008b) and the South Eastern Pyrenees where it is documented in Balma Guilanyà (Martínez-Moreno et al. 2010). Our results fall within the variability range of the cited examples, which, adopting Whallon's model, would correspond to interactions taking place within minimal bands (distances up to 28 km), within maximal bands (up to distances of 123 km) and, to a lesser extent, between different maximal bands (up to 325 km). The extent to which links above 325 km do represent interactions beyond adjacent maximal bands remains to be further investigated, using additional and more accurately traceable raw material evidence.

The centrality analysis of our networks allowed us to relate assemblage composition to the interaction structures. In particular, assemblages sharing a very similar composition with several other assemblages in the network present simultaneously higher degree and weighted degree centralities. Conversely, nodes with high betweenness corresponded to assemblages including uncommon ornament combinations, thus becoming the bridges amongst assemblages with complementary compositions.

Specifically, we found that in the Late Mesolithic network, the nodes with the highest betweenness drew an arc connecting the Mediterranean sites, through the Ebro Valley to the Cantabrian sites. This suggests that sites in the Ebro Valley may have bridged indirect interactions between Mediterranean and Cantabrian groups, in agreement with a common conception of the Ebro Valley as a communication route between these two regions (Alday 2002; Cava 2004; Alday 2006; Álvarez Fernández 2008a; Alday and Cava Almuzara 2009; Álvarez Fernández 2014). Despite of the archaeological evidence that suggests the Ebro Valley was part of a network that connected groups from distant regions in the Iberian Peninsula, the interpretation of our results (i.e. the betweenness values) should be treated with caution. Centrality measures generally (and betweenness, in particular) are known to be affected by record incompleteness (Peeples et al. 2016). Indeed, the fact that in the Early Mesolithic network the betweenness values do not suggest that the Ebro Valley played an important role in the circulation of ornaments may be related to the sensibility of the betweenness metric.

Researchers in archaeology are aware of the limitations of the application of SNA to archaeological studies. Different approaches have been designed to overcome them. Most of these approaches are devoted to quantifying the extent to which missing data affects the network analysis (e.g. Gjesfjeld 2015), or to designing procedures that may help identify missing links within networks (Tsirogiannis and Tsirogiannis 2016). To our mind, the best course of action to pursue the line of investigation inaugurated in the present work is to incorporate geographical and environmental

information into the network analysis. More concretely, the approach applied by Gravel-Miguel (2016), which integrates biome reconstructions with social network analyses during the Magdalenian in the Cantabrian region, lead to a more accurate appreciation of human mobility, intra-regional and interregional interaction patterns against the environmental changes of the Last Glacial Maximum.

Conclusions

Our primary objective was to reconstruct and analyse the interaction patterns amongst groups in the Iberian Mesolithic. For this, we constructed and analysed socio-spatial networks using ornaments as a proxy for human interactions. Moreover, this case study was an opportunity to evaluate the potential of SNA in prehistoric hunter-gatherer research.

Our findings suggest that despite climatic, cultural and population transformations, general patterns of human interactions remained unaltered between the two culturally different phases of the Iberian Mesolithic. We also observed the emergence of spatial patterns of interaction, in which most interactions potentially took place within a radius of 300 km. Based on Whallon's (2006) heuristic model of the spatial organisation of band-level foraging groups, we believe that these findings have captured the interactions that took place mainly within maximum bands, and between groups belonging to different maximum bands.

These analyses have required the introduction of two methodological contributions that are novel to the application of SNA in prehistoric archaeology. First, in order to incorporate as much reliable archaeological data as possible, we developed a procedure that classifies the information according to its chrono-cultural reliability (see 'Data Collection' subsection within the 'Data and Methods' section). It is common practice amongst scholars using archaeological data to construct networks, to accept its chrono-cultural reliability as stated by the original researchers. However, when the corpus of data is the results of a long research tradition and has been produced by different teams (as it is our case in this article), one cannot assume a homogeneous level of accuracy across the dataset. This evidences the need for a protocol, such as the one presented here. The second innovative contribution was to apply assortativity to quantitatively measure regionalization in our networks. The usage of this homophily metric (quite common in SNA application outside archaeology) allowed us to compare regionalisation across the two periods beyond visual inspection of the obtained networks.

We also encountered a few limitations to the research approach applied, which are not exclusive to our case study. Indeed, they derive from the specific nature of the Palaeolithic archaeological record, which is fragmentary and biased in

its nature. This poses a challenge to archaeologists. As many aspects of prehistoric human life, socio-spatial structure can only be well understood by considering multiple lines of evidence. Although the research presented in this paper is highly informative, the addition of different archaeological proxies and environmental information could build upon the present case study and further increase our knowledge of Mesolithic hunter-gatherer societies. The present case study not only demonstrates the potential of applying SNA to the interaction patterns of Iberian Mesolithic human groups, but it also indicates the direction to follow within this line of research.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12520-022-01641-z>.

Code availability The code in R language used to perform the analysis, as well as the required input files, have been uploaded to the Zenodo repository with <https://doi.org/10.5281/zenodo.6982854>.

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Data availability All data needed to reproduce this work are provided in the Supplementary Materials.

Declarations

Competing interests The authors declare no competing interests.

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References

- Alday A (2006) El Mesolítico de muescas y denticulados en la cuenca del Ebro y el litoral mediterráneo peninsular: síntesis de los datos. In: Alday A (ed) *Mesolítico de muescas y denticulados en la cuenca del Ebro y el litoral mediterráneo peninsular*. Diputación Foral de Álava, departamento de Cultura, pp 303–317
- Alday A (2002) Las unidades industriales mesolíticas en la alta-media cuenca del Ebro. *Complutum* 13:19–50
- Alday A, Cava Almuzara A (2006) La unidad de Muecas y Denticulados del Mesolítico en el País Vasco: la formalización de un modelo cultural. In: Alday A (ed) *El mesolítico de muescas y denticulados en la cuenca del Ebro y el litoral mediterráneo peninsular*. Diputación Foral de Álava, Departamento de Cultura, pp 223–300
- Alday A, Cava Almuzara A (2009) El Mesolítico Geométrico en Vasconia. *El Mesolítico geométrico en la Península ibérica Monogr. Arqueol* 44:93–130
- Alday A, Soto A (2017) La Sociedad Mesolítica de la Península Ibérica. In: Pérez-Díaz S, Ruiz-Fernández J, López-Sáez J-A, García-Hernández C (eds) *Cambio climático y cultural en la Península Ibérica: una perspectiva geohistórica y paleoambiental*. Universidad de Oviedo, Oviedo, pp 75–91
- Álvarez-Fernández E (2006) Los objetos de adorno-colgantes del Paleolítico superior y del Mesolítico en la Cornisa Cantábrica y en el Valle del Ebro: una visión europea. Universidad de Salamanca
- Álvarez-Fernández E (2010) Shell beads of the last hunter-gatherers and earliest farmers in south-western Europe. *MUNIBE (Antropología-Arkeología)* 61:129–138
- Álvarez Fernández E (2011) Personal ornaments made from mollusc shells in Europe during the Upper Palaeolithic and Mesolithic: news and views. In: Cakirlar C (ed) *Archaeomalacology revisited*. Oxbow Books, pp 1–8
- Álvarez Fernández E (2008a) The use of *Columbella rustica* (class: gastropoda) in the Iberian Peninsula and Europe during the Mesolithic and the early Neolithic. *IV Congr del Neolítico Penins* 2:103–111
- Álvarez Fernández E (2001) Perforated *Homalopoma sanguineum* from Tito Bustillo (Asturias): mobility of Magdalenian groups in northern Spain. *Antiquity* 76:641–646
- Álvarez Fernández E (2008b) The use of *Columbella rustica* (class: gastropoda) in the Iberian Peninsula and Europe during the Mesolithic and the early Neolithic. In: Hernández Pérez M, Soler Díaz J, López Padilla JA (eds) *IV Congreso del Neolítico Peninsular: 27-30 de noviembre de 2006*. pp 103–111
- Álvarez Fernández E (2014) Indicios de redes de intercambio en Forcas II: las conchas de moluscos marinos. In: Utrilla P, Mazo C (eds) *La Peña de las Forcas (Graus, Huesca) Un asentamiento estratégico en la confluencia del Ésera y el Isábena*. Monografías Arqueológicas. Prehistoria, 46 Universidad de Zaragoza, pp 323–328
- Arias Cabal P, Fano MÁ (2009) ¿Mesolítico geométrico o Mesolítico con geométricos? El caso de la región cantábrica. In: Utrilla P, Montes L (eds) *El Mesolítico geométrico en la Península Ibérica*. Universidad de Zaragoza, Departamento de Ciencias de la Antigüedad, Zaragoza, pp 69–91
- Aura JE, Jordá JF, Montes L, Utrilla P (2011) Human responses to Younger Dryas in the Ebro valley and Mediterranean watershed (Eastern Spain). *Quat Int* 242:348–359. <https://doi.org/10.1016/J.QUAINT.2011.01.023>
- Aura JE, Jordá Pardo JF, Morales JV et al (2009) Economic transitions in finis terra : the western Mediterranean of Iberia. *Before Farming* 2:1–17
- Aura Tortosa JE, Jordà Pardo FJ, Pérez M, et al (2009) Epipaleolítico y Mesolítico en Andalucía Oriental primeras notas a partir de los datos de la Cueva de Nerja (Málaga, España). In: Utrilla P, Montes L (eds) *El Mesolítico geométrico en la Península Ibérica*. pp 343–360
- Balsera V, Díaz-del-Río P, Gilman A et al (2015) Approaching the demography of late prehistoric Iberia through summed calibrated date probability distributions (7000–2000 cal BC). *Quat Int* 386:208–211. <https://doi.org/10.1016/j.quaint.2015.06.022>
- Barton CM, Aura Tortosa JE, García-Puchol O et al (2018) Risk and resilience in the late glacial: a case study from the western Mediterranean. *Quat Sci Rev* 184:68–84. <https://doi.org/10.1016/j.quascirev.2017.09.015>

- Bicho N, Haws J (2012) The Magdalenian in central and southern Portugal: human ecology at the end of the Pleistocene. *Quat Int* 272–273:6–16. <https://doi.org/10.1016/j.quaint.2012.02.055>
- Birch J, Hart JP (2018) Social networks and northern Iroquoian confederacy dynamics. *Am Antiq* 83(1):13–33
- Boric D, Cristiani E (2016) Social networks and connectivity among the palaeolithic and mesolithic foragers of the Balkans and Italy. In: Krauss R, Floss H (eds) *Southeast Europe before neolithisation. Proceedings of the International Workshop within the Collaborative Research Centres sfb 1070 “RessourcenKulturen”, Schloss Hohentübingen, 9th of May 2014. Universität Tübingen*, pp 73–112
- Brandes U, Wagner D (2004) Analysis and visualization of social networks. In: *Graph drawing software*. Springer, pp 321–340
- Brughmans T, Collar A, Coward F (2016) *The connected past challenges to network studies in archaeology and history*. Oxford University Press, Oxford
- Buchanan B, Hamilton MJ, David Kilby J (2019) The small-world topology of Clovis lithic networks. *Archaeol Anthropol Sci* 11:3537–3548. <https://doi.org/10.1007/s12520-018-0767-7>
- Cacho C, Martos JA, Jordá Pardo J et al (2010) El Paleolítico superior en el interior de la Península Ibérica. Reflexión crítica y perspectivas de futuro. In: Mangado X (ed) *El Paleolítico superior peninsular. Novedades del siglo XXI, vol 8. Monografías del Seminari d’Estudis i Recerques Prehistòriques, Barcelona*, pp 75–96
- Cacho I, Grimalt JO, Canals M et al (2001) Variability of the western Mediterranean Sea surface temperature during the last 25,000 years and its connection with the Northern Hemisphere climatic changes. *Paleoceanography* 16:40–52. <https://doi.org/10.1029/2000PA000502>
- Carrión JS, Fernández S, González-Sampériz P et al (2010) Expected trends and surprises in the Lateglacial and Holocene vegetation history of the Iberian Peninsula and Balearic Islands. *Rev Palaeobot Palynol* 162:458–475. <https://doi.org/10.1016/j.revpalbo.2009.12.007>
- Carvalho AF (2010) Chronology and geography of the Mesolithic-Neolithic transition in Portugal. In: Armbruster T, Hegewisch M (eds) *On pre- and earlier history of Iberia and Central Europe studies in honour of Philine Kalb. Studien Tuidien zur Archäologie, Europas 11. Dr. Rudolf Habelt GmbH, Bonn*, pp 45–62
- Cava A (2004) Los “procesos culturales” del comienzo del holoceno en la cuenca del Ebro y su contextualización. *Saldvie* 4:17–40
- Collar A, Coward F, Brughmans T, Mills BJ (2015) Networks in archaeology: phenomena, abstraction, representation. *J Archaeol Method Theory* 22:1–32. <https://doi.org/10.1007/s10816-014-9235-6>
- Cortés Sánchez M (2007) *Cueva Bajondillo (Torremolinos). Secuencia cronocultural y paleoambiental del Cuaternario reciente de la bahía de Málaga. Servicio de Publicaciones y Divulgación Científica de la Universidad de Málaga*
- Coward F (2010) Small worlds, material culture and ancient near eastern social networks. In: Dunbar R, Gamble C, Gowlett J (eds) *Social brain, distributed mind*. Oxford University Press, Oxford, pp 453–483
- Csardi G, NT (2006) *The igraph software package for complex network research*
- Escobar Requena A (2010) *Tras las huellas del cambio en el centro peninsular. La industria de muescas y denticulados del yacimiento Parque Darwin (Madrid) en el contexto del IX milenio BP. Universidad Autónoma de Madrid*
- Evans S, Felder K (2016) Introduction: making the connection: changing perspectives on social networks. *Archaeol Rev from Cambridge* 29:9–17
- Fernández-López de Pablo J, Gómez-Puche M (2009) Climate change and population dynamics during the Late Mesolithic and the Neolithic transition in Iberia. *Doc Prehist* 36:67–96
- Fernández-López de Pablo J, Gutiérrez-Roig M, Gómez-Puche M et al (2019) Palaeodemographic modelling supports a population bottleneck during the Pleistocene-Holocene transition in Iberia. *Nat Commun* 10:1872. <https://doi.org/10.1038/s41467-019-09833-3>
- Fernández-López de Pablo J, Jochim MA (2010) The impact of the 8,200 Cal BP climatic event on human mobility strategies during the Iberian Late Mesolithic. *J Anthropol Res* 66:39–68
- Freeman LC (1979) Centrality in social networks conceptual clarification. *Soc Networks* 1:215–239. [https://doi.org/10.1016/0378-8733\(78\)90021-7](https://doi.org/10.1016/0378-8733(78)90021-7)
- Fruchterman TM, Reingold E (1991) Graph drawing by force-directed placement. *Software-Practice Exp* 21:1129–1164
- Gamble C (1998) Palaeolithic society and the release from proximity: a network approach to intimate relations. *World Archaeol* 29:426–449. <https://doi.org/10.1080/00438243.1998.9980389>
- García-Martínez de Lagrán I, Rojo-Guerra MA, Iriarte E et al (2014) Paleoaambiente y cambios culturales en los inicios del Holoceno: el abrigo de Artusia (Unzué, Navarra). *Trab Arqueol Navarra* 26:7–98
- Gibaja JF, Subirà ME, Terradas X et al (2015) The emergence of mesolithic cemeteries in SW Europe: insights from the El Collado (Oliva, Valencia, Spain) *Radiocarbon Record. PLoS One* 10:1–18
- Gjesfjeld E (2015) Network analysis of archaeological data from hunter-gatherers: methodological problems and potential solutions. *J Archaeol Method Theory* 22:182–205. <https://doi.org/10.1007/s10816-014-9232-9>
- Gomes SD, Fletcher WJ, Rodrigues T et al (2020) Time-transgressive Holocene maximum of temperate and Mediterranean forest development across the Iberian Peninsula reflects orbital forcing. *Palaeogeogr Palaeoclimatol Palaeoecol* 550:109739. <https://doi.org/10.1016/j.palaeo.2020.109739>
- González-Sampériz P, Utrilla P, Mazo C et al (2009) Patterns of human occupation during the early Holocene in the Central Ebro Basin (NE Spain) in response to the 8.2 ka climatic event. *Quat Res* 71:121–132. <https://doi.org/10.1016/j.yqres.2008.10.006>
- Gravel-Miguel C (2016) Using species distribution modeling to contextualize Lower Magdalenian social networks visible through portable art stylistic similarities in the Cantabrian region (Spain). *Quat Int* 412:112–123. <https://doi.org/10.1016/j.quaint.2015.08.029>
- Gravel-Miguel C, Coward F (2021) Palaeolithic social networks and behavioural modernity. In: Brughmans, T., Mills, B., Munson, J. and Peeples, M., eds. *The Oxford Handbook of Archaeological Network Research*. Oxford: Oxford University Press. (In Press)
- Hamilton MJ, Milne BT, Walker RS et al (2007) The complex structure of hunter-gatherer social networks. *Proc R Soc B Biol Sci* 274:2195–2203. <https://doi.org/10.1098/rspb.2007.0564>
- Hammer Ø, Harper DAT, Ryan PD (2001) *Past: Paleontological statistics software package for education and data analysis*
- Hart JP, Birch J, Gates St-Pierre C (2017) Effects of population dispersal on regional signaling networks: an example from northern Iroquoia. *Sci Adv* 3(8):e1700497
- Kandler A, Caccioli F (2016) Networks, homophily, and the spread of innovation. In: Brughmans T, Collar A, Coward F (eds) *The connected past. Challenges to Network Studies in Archaeology and History2*. Oxford University Press, Oxford, pp 175–199
- Knappett C (2011) *An archaeology of interaction. Network perspectives on material culture and society*. Oxford University Press, Oxford
- Knappett C (2013) *Network analysis in archaeology. New Approaches to Regional Interaction*. Oxford University Press, Oxford
- López-Sáez J-A, López-Merino L, Pérez Díaz S (2007) Crisis climáticas en la Prehistoria de la Península Ibérica: el Evento 8200 cal. BP como modelo. In: Salvador Rovira L, Heras GM, Moret Gener M, Ruiz Montero I (eds) *Actas VII Congreso Ibérico de Arqueometría (Madrid). Consejo Superior de Investigaciones Científicas (España, Madrid)*, pp 77–86
- Martí Oliver B, Aura Tortosa JE, Juan Cabanilles J et al (2009) El Mesolítico Geométrico de tipo “Cocina” en el País Valenciano. In: *El mesolítico Geométrico en la Península Ibérica. Monografía, Zaragoza-Jaca*, pp 205–258

- Martínez-Moreno J, Mora R, Casanova J (2010) Lost in the mountains? Marine ornaments in the Mesolithic of the northeast of the Iberian Peninsula. *Munibe*, Supl 30:100–109
- Mazzucato C (2019) Socio-material archaeological networks at Çatalhöyük a community detection approach. *Front Digit Humanit* 6:8. <https://doi.org/10.3389/fgdigh.2019.00008>
- McLaughlin TR, Gómez-Puche M, Cascallheira J et al (2021) Late Glacial and Early Holocene human demographic responses to climatic and environmental change in Atlantic Iberia. *Philos Trans R Soc B Biol Sci* 376:20190724. <https://doi.org/10.1098/rstb.2019.0724>
- Mills BJ (2017) Social network analysis in archaeology. *Annu Rev Anthropol* 46:379–397. <https://doi.org/10.1146/annurev-anthro-102116-041423>
- Montes L, Utrilla P, Mazo C (2006) El Epipaleolítico macrolítico en Aragón en el contexto del valle del Ebro y la Cataluña costera. In: El mesolítico de muescas y denticulados en la cuenca del Ebro y el litoral mediterráneo peninsular
- Newell RR, Kielman D, Constandse-Westermann TS, et al (1990) An inquiry into the ethnic resolution of Mesolithic regional groups : the study of their decorative ornaments in time and space, E.J. Brill. E.J. Brill, Leiden
- Newman MEJ (2002) Assortative mixing in networks. *Phys Rev Lett* 89:208701. <https://doi.org/10.1103/PhysRevLett.89.208701>
- Peeples MA (2019) Finding a place for networks in archaeology. *J Archaeol Res* 27:451–499. <https://doi.org/10.1007/s10814-019-09127-8>
- Peeples MA, Mills BJ, Haas RW et al (2016) Analytical challenges for the application of social network analysis in archaeology. In: Brughmans T, Collar A, Coward F (eds) *The connected past. Challenges to Network Studies in Archaeology and History*. Oxford university Press, Oxford, p 200
- Peltier WR (2002) On eustatic sea level history: Last glacial maximum to Holocene. *Quat Sci Rev* 21:377–396
- Perlès C (2019) Special issue: early personal ornaments --- cultural implications of uniformity in ornament assemblages: Paleolithic and Mesolithic ornaments from Franchthi Cave. *PaleoAnthropology* 2019:196–207
- Perlès C (2013) Tempi of change: when soloists don't play together. Arrhythmia in 'Continuous' Change. *J Archaeol Method Theory* 20:281–299
- Prignano L, Morer I, Diaz-Guilera A (2017) Wiring the past: a network science perspective on the challenge of archeological similarity networks. *Front Digit Humanit* 4:13. <https://doi.org/10.3389/fgdigh.2017.00013>
- QGIS.org (2021) QGIS geographic information system
- Riede F (2014) Eruptions and ruptures – a social network perspective on vulnerability and impact of the Laacher See eruption (c. 13,000 BP) on Late Glacial hunter-gatherers in northern Europe. *Archaeol Rev from Cambridge* 29:67–102
- Rigaud S, d'Errico F, Vanhaeren M (2015) Ornaments reveal resistance of North European cultures to the spread of farming. *PLoS One* 10:e0121166
- Rigaud S, Gutiérrez-Zugasti I (2016) Symbolism among the last hunter–fisher–gatherers in northern Iberia: personal ornaments from El Mazo and El Toral III Mesolithic shell midden sites. *Quat Int* 407:131–144. <https://doi.org/10.1016/J.QUAINT.2015.10.029>
- Rigaud S, Manen C, de Lagrán I (2018) Symbols in motion: flexible cultural boundaries and the fast spread of the Neolithic in the western Mediterranean. *PLoS One* 13:1–18. <https://doi.org/10.1371/journal.pone.0196488>
- Rivero O, Sauvet G (2014) Defining Magdalenian cultural groups in Franco-Cantabria by the formal analysis of portable artworks. *Antiquity* 88:64–80. <https://doi.org/10.1017/S0003598X00050225>
- Romano V, Lozano S, Fernández-López de Pablo J (2020) A multilevel analytical framework for studying cultural evolution in prehistoric hunter–gatherer societies. *Biol Rev*
- Scott J (2017) *Social network analysis*. Fourth, 55 City Road, London: SAGE Publications Ltd. <https://doi.org/10.4135/9781529716597>
- Soto A, Alday A, Montes L et al (2015) Epipalaeolithic assemblages in the Western Ebro Basin (Spain): the difficult identification of cultural entities. *Quat Int* 364:144–152
- Stiner MC (2014) Finding a common bandwidth: causes of convergence and diversity in Paleolithic beads. *Biol Theory* 9:51–64. <https://doi.org/10.1007/s13752-013-0157-4>
- Straus LG (2018) Environmental and cultural changes across the Pleistocene–Holocene transition in Cantabrian Spain. *Quat Int* 465:222–233. <https://doi.org/10.1016/j.quaint.2016.10.005>
- Team RC (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing
- Tejero J-M, Bar-Oz G, Bar-Yosef O et al (2021a) New insights into the Upper Palaeolithic of the Caucasus through the study of personal ornaments. Teeth and bones pendants from Satsurbli and Dzudzuanava caves (Imereti, Georgia). *PLoS One* 16:1–30. <https://doi.org/10.1371/journal.pone.0258974>
- Tejero J-M, Rabinovich R, Yeshurun R et al (2021b) Personal ornaments from Hayonim and Manot caves (Israel) hint at symbolic ties between the Levantine and the European Aurignacian. *J Hum Evol* 160:102870. <https://doi.org/10.1016/j.jhevol.2020.102870>
- Thompson AE, Feinman GM, Lemly M, Prufer KM (2021) Inequality, networks, and the financing of Classic Maya political power. *J Archaeol Sci* 133:105441. <https://doi.org/10.1016/j.jas.2021.105441>
- Tsirogiannis C, Tsirogiannis C (2016) Uncovering the hidden routes: algorithms for identifying paths and missing links in trade networks. In: Brughmans T, Collar A, Coward F (eds) *The connected past. Challenges to Network Studies in Archaeology and History*. Oxford University Press, Oxford, pp 103–122
- Utrilla P, Montes L (2009) El Mesolítico geométrico en la Península Ibérica. Universidad de Zaragoza, Departamento de Ciencias de la Antigüedad, Zaragoza
- Vanhaeren M, d'Errico F (2006) Aurignacian ethno-linguistic geography of Europe revealed by personal ornaments. *J Archaeol Sci* 33:1105–1128. <https://doi.org/10.1016/j.jas.2005.11.017>
- West DB (1996) *Introduction to Graph Theory*. Prentice Hall, Upper Saddle River, N.J.
- Whallon R (2006) Social networks and information: Non-“utilitarian” mobility among hunter-gatherers. *J Anthropol Archaeol* 25:259–270. <https://doi.org/10.1016/j.jaa.2005.11.004>
- Wiessner P (1984) Reconsidering the behavioral basis for style: a case study among the Kalahari San. *J Anthropol Archaeol* 3:190–234. [https://doi.org/10.1016/0278-4165\(84\)90002-3](https://doi.org/10.1016/0278-4165(84)90002-3)
- Wobst HM (1976) Locational relationships in Paleolithic society. *J Hum Evol* 5:49–58. [https://doi.org/10.1016/0047-2484\(76\)90099-3](https://doi.org/10.1016/0047-2484(76)90099-3)
- Wobst HM (1974) Boundary conditions for Paleolithic social systems: a simulation approach. *Soc Am Archaeol Am Antiq* 39:147–178
- Zilhão J (2001) Radiocarbon evidence for maritime pioneer colonization at the origins of farming in west Mediterranean Europe. *Proc Natl Acad Sci* 98:14180 LP–1414185. <https://doi.org/10.1073/pnas.241522898>

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