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Evidence from personal ornaments suggest nine distinct cultural groups between 34,000 and 24,000 years ago in Europe

In the format provided by the authors and unedited

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Supplementary Results – **Modularity test and permutational MANOVA**

The materials, methods and results of the cluster detection algorithms and perMANOVA used to assess the goodness of fit of our seriation sets.

Supplementary Results – **Modelling the effect of spatial and cultural boundaries**

The materials, methods and results of the Mantel test modelling used to assess the effects of different strength barriers on the Mantel test result.

Modularity test and permutational MANOVA

In order to assess the significance of the groups identified by the seriations, we performed two complimentary analysis, a Modularity[1] test and a Permutational Multivariate Analysis of Variance (perMANOVA)[2,3]. To perform the tests, we only took into account sites that share a non-zero similarity index value with at least another site, and which belong to one of the groups identified by the seriation.

To test the effect of time on the bead-type diversity of the occupation dataset we also performed a perMANOVA on the sites attributed to one Gravettian phase (Early, Middle, Late). We have excluded occupation sites with unreliable chronological attribution from the dataset.

Modularity describes how the structure of a group is divided into distinct subgroups or clusters[4]. The result is given by a Modularity score ranging from 0 (no significant subgroups) to 1 (perfect clusters). The Modularity score was then compared to the score obtained for groups created by three cluster detection algorithms (the Girvan-Newman[5], the Walktrap[6] and the Louvain modularity[7]). The necessary network computation and Modularity tests were performed using code adapted from Pereira et al. (2023)[8] and Brughmans and Peeples (2023)[9], respectively.

PerMANOVA is a non-parametric test of significant difference between two or more groups, based on any distance measure. The result is expressed as an R^2 statistic. The test was performed in *R* statistical environment[10,11].

Results

The groups identified by the seriation analysis on the occupation dataset show a low modularity score of 0.1493 (Supplementary Table 1). This score is lower than those obtained by the three cluster algorithms. The modularity score calculated for the burial dataset is higher (0.3058) and close to the scores obtained by the three cluster algorithms (Supplementary Table 1).

Comparison of the two modularity scores (Occupations = 0.149300999864272, Burials = 0.3058665) to the scores calculated by the clustering algorithm show that the groups identified by the burial dataset seriation are more significant than those identified by the occupation dataset seriation.

	Seriation groups	Girvan-Newman	Walktrap	Louvain
Occupations	0.149300999864272	0.270283986631758	0.280503925298356	0.363526296843435
Burials	0.3058665	0.3110849	0.2863816	0.3432792

Supplementary Table 1 – Modularity scores calculated to assess the significance of the groups identified by the seriations performed on the occupation and burial datasets.

The perMANOVA performed on the groups identified by the seriation on the occupation dataset shows a statistically significant R^2 (5) = 0.1407 (p-value = 0.001) with an F-model of 2.6526085921875 (Supplementary Table 2), indicating that the groups explain 14% of the variation in the data. The perMANOVA applied to the burial dataset groups shows a statistically significant R^2 (2) = 0.5334 (p-value = 0.001) with a F-model of 12.573473809086 (Supplementary Table 2), indicating that groups identified by the seriation analysis explain 53.34% of the variance in the data.

The F-model[2] (*i.e.*, the ratio of between and within set variation) calculated by the perMANOVA (Supplementary Table 2) indicates that the burial dataset have a higher between-groups variation compared to within-groups variation than the occupation dataset. It shows that the groups identified by the seriation performed on the burial dataset are more distinct from one another than the groups identified by the seriation performed on the occupation dataset.

	R^2	P-value	F-model
Occupations	0.14070246985803	0.001	2.6526085921875
Burials	0.533373821394103	0.001	12.573473809086

Supplementary Table 2 – Results of the one-tailed perMANOVA calculated to assess the significance of the groups identified by the seriations performed on the occupation and burial datasets.

The amount of variance of bead-type associations explained by the chronological phasing of the Gravettian is significant but low (R^2 (2) = 0.055, p = 0.005) while the groups identified by the seriation explain 15% of the variance in the data (R^2 (4) = 0.15328035653664, p = 0.001), a value very similar to the result obtain on the full dataset (Supplementary Table 3).

The F-model statistics confirm that the groups identified by the seriation show a higher between-groups variation than the chronological phasing.

	R^2	P-value	F-model
Reduced occupation dataset ~ Seriation groups	0.15328035653664	0.001	2.30811291663003
Reduced occupation dataset ~ Gravettian chronological phases	0.0550199468252677	0.005	1.54291996531698

Supplementary Table 3 – Results of the one-tailed perMANOVA calculated to assess the significance of the groups identified by the seriations performed on the occupation reduced datasets and the significance of the bead-type diversity identified between the 3 phases of the Gravettian (Early, Middle, Late).

Modelling the effect of spatial and cultural boundaries

Methodology

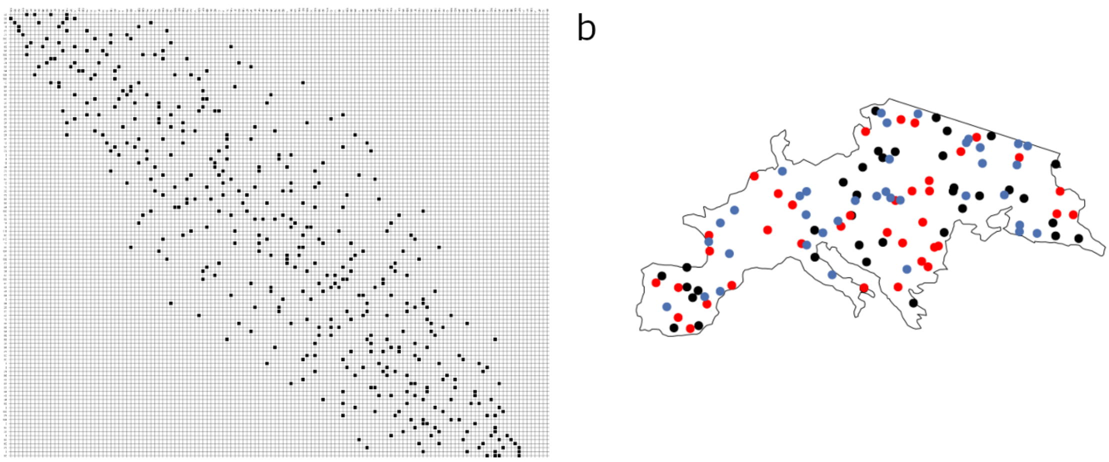
We modeled the effects of different strength barriers on the Mantel test Z value (R^2) score by creating and analysing five simulated datasets to explore bead-type diversity in three synthetic Gravettian cultural groups using different bead-type associations across mainland Europe[12]. The sample includes 111 sites generated to fit a number of different spatial distributions. The main experiment considered sites distributed so as to fit a random *Poisson* spatial point pattern, and thus fulfilling the criteria of Complete Spatial Randomness (CSR)[13,14]. This implies that no spatial correlation exists between the three groups, *i.e.*, they are independently and uniformly distributed across the spatial window. For each additional experiment, restrictions were imposed on the distribution of sites according to the objectives of the model.

For the cultural attributes of each of these groups, we simulated a matrix with similar dimensions to our combined (occupation and burial) dataset. These matrices were thus defined to have a shape of ≈ 111 × 135 (111 sites and 135 bead-types). Their content were filled in by using a Monte Carlo sampling of hypothetical discrete probability density functions. The reason for not using the precise size of our empirical dataset was simply that dividing these values by the three available groups is easier computationally. The means in which the simulation of site features were calculated considered each site to have the ability to sample a random set of values from the proposed discrete multinomial probability distribution. The sampled value indicates the type of bead-types present in each specific site. Sampling algorithms were conditioned so that each site can present up to 4 different types of beads, while all other types would thus be considered absent. The value of 4 was chosen as it is the mean sum of all of the types of beads present across the sites in the real archaeological datasets.

Model 1 – Random spatial and cultural attributes

This simulation reflects the hypothetical situation in which no spatial and cultural barriers affect bead-type associations (Supplementary Fig. 1). Sites were attributed coordinate values randomly, *i.e.* the nature of this spatial distribution would fall under the category of CSR, in which the presence of one group is completely uncorrelated with the presence of other groups[15,16]. Similarly, the bead-types sampling was done to emulate the effect of no group having a preference for any particular bead-types. Under this premise, every site has a 0.74% chance of picking up a particular bead-type.

a

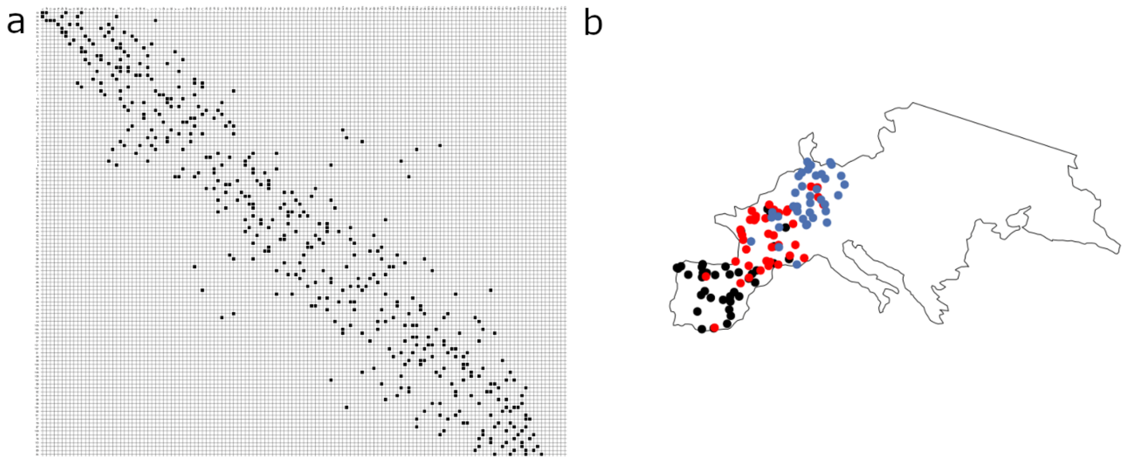


b

Supplementary Figure 1 – Model 1, Random spatial and cultural attributes: a) seriation of the simulated sites (left) and beads (top), b) geographical distribution of the three groups of sites across Europe.

Model 2 – Slight spatial overlap and partially shared cultural attributes

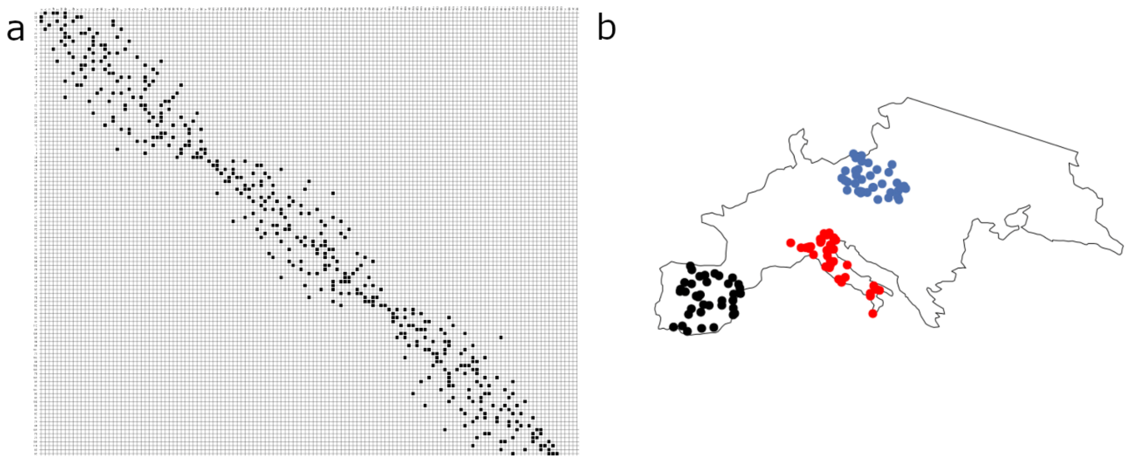
The purpose of this simulation is to propose a hypothetical situation in which populations are characterized by slight overlapping in their spatial distribution and by partially shared material culture (Supplementary Fig. 2). This model entails a slight spatial attraction between the three modeled groups[15,16], and intra-group CSR. Regarding the nature of the beads associated with each group, we assigned a 90% probability for Group 1 to be associated with beads of type 1 to 45, and a 10% probability of being associated with beads of type 46 to 135. Similarly, Group 2 was set to have a 90% probability of being associated with beads of type 46 to 90, Group 3 with a 90% probability of being associated with beads of type 91 to 135, and so forth.



Supplementary Figure 2 – Model 2, Slight spatial overlap and partially shared cultural attributes*: a) seriation of the simulated sites (left) and beads (top), b) geographical distribution of the three groups of sites across Europe.*

Model 3 – Marked spatial and cultural boundaries

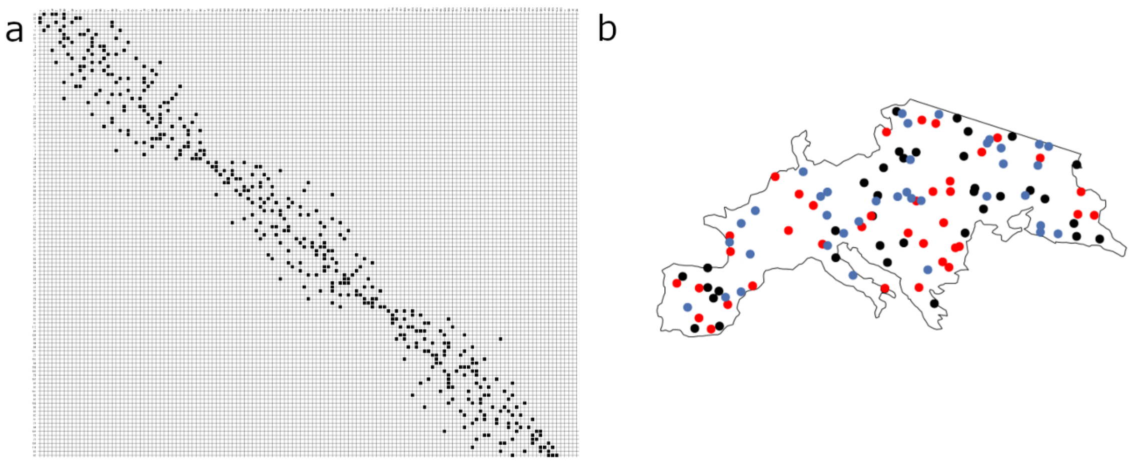
The purpose of this simulation is to propose an ideal example of bead-type associations determined by strong spatial and cultural boundaries (Supplementary Fig. 3). To achieve this, we simulated three groups occupying clearly separate regions, i.e. with the spatial distribution of points identifying one group repelling those of the other groups[15,16]. In this scenario, the groups were also modelled to have no cultural similarities between themselves. The probability of Group 1 presenting a bead-type 46 to 135 was set to 0%, Group 2 had a 0% probability of presenting bead-types 1 to 45 and 91 to 135, and Group 3 had a 0% probability of presenting bead-types 1 to 90.



Supplementary Figure 3 – Model 3, Marked spatial and cultural boundaries: a) seriation of the simulated sites (left) and beads (top), b) geographical distribution of the three groups of sites across Europe.

Model 4 – Distinct cultural attributes, random spatial distribution

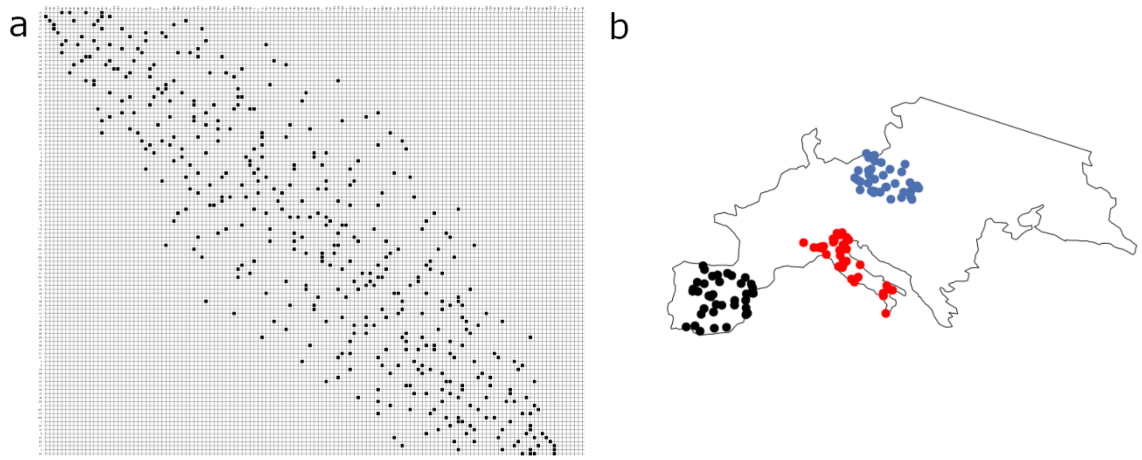
The purpose of this model is to create a hybrid of models 1 and 3, in which the spatial distribution of sites adheres to CSR, and the three groups have no cultural similarities between them (Fig. 4). Specifically, the probability of Group 1 presenting a bead of type 46 through to 135 was set to 0%, while types 1 through to 45 were set to 100%, and so for the other groups.



Supplementary Figure 4 – Model 4, Distinct cultural Attributes, random spatial distribution: a) seriation of the simulated sites (left) and beads (top), b) geographical distribution of the three groups of sites across Europe.

Model 5 – Random cultural attributes, marked spatial boundaries

The purpose of this simulation is to hybridize models 1 and 3, in which the groups were simulated to exhibit clear isolation in space (spatial inhibition), while the cultural attributes were randomly generated (Supplementary Fig. 5). Similar to Model 1, every site in this simulation has a 0.74% chance of presenting each bead-type.



Supplementary Figure 5 – Model 5, Random cultural attributes, marked spatial boundaries: a) seriation of the simulated sites (left) and beads (top), b) geographical distribution of the three groups of sites across Europe.

Mantel tests

Jaccard dissimilarity values were calculated for each simulation from the matrices of cultural attributes. The great circle distance was used to calculate the geographic distance between sites. Mantel tests were conducted on each of the simulated datasets so as to assess the relationship between these features. All simulations were performed using the base R (v.4.3.0) programming language. Simulating random coordinate values was facilitated by the spatstat (v.3.0) library[13].

Results

The five models produce notably different Mantel test Z values (Supplementary Table 4). Model 1 (Mantel Z Value (109) = -0.01053, p = 0.7885), Model 4 (Mantel Z Value (109) = -0.009945, p = 0.8093) and Model 5 (Mantel Z Value (109) = -0.01871, p = 0.9318) each result in a non-significant, low and negative Mantel test Z value. Model 2, which assumes a slight geographical overlap of sites with partially shared cultural attributes, yields a low but significant Mantel test Z value (Mantel Z Value (109) = 0.1296, p = < 0.001). Model 3, which assumes a clear separation of geographical and cultural traits, results in a relatively strong and significant Mantel test Z value (Mantel Z Value (109) = 0.3517, p = < 0.001).

Model	Z value (R^2)	P-Value
Model 1 – Random spatial and cultural attributes	-0.01053	0.7885
Model 2 – Slight spatial overlap and partially shared cultural attributes	0.1296	< 0.001
Model 3 – Marked spatial and cultural boundaries	0.3517	< 0.001
Model 4 – Different cultural attributes, random spatial distribution	-0.009945	0.8093
Model 5 – Random cultural attributes, marked spatial boundaries	-0.01871	0.9318

Supplementary Table 4 – Results of the two-tailed mantel tests performed on the datasets generated by the five simulations.

Model 1, Model 4 and Model 5 produce Mantel Z values that are substantially different from any of our real archaeological data results (see Table 1 main text). Model 2 and Model 3 produce results that are comparable to Mantel test Z values obtained for Gravettian occupation and burial datasets respectively.

The result of Model 2 indicates that the bead-type associations identified in the Gravettian occupation dataset conform to a scenario in which neighboring cultural entities characterized by specific bead-types shared some of them with neighboring groups, with synchronically or diachronically fluctuating boundaries.

The result of Model 3 indicates that the bead-type associations identified in the Gravettian burial dataset is consistent with a scenario in which geographically distinct groups use different bead-types. Although the highest Mantel Z value produced by this simulation theoretically indicates isolation by geographic distance being a main driver of the archaeological bead diversity, this hypothesis is contradicted, in our case, by the temporal divide between the identified burial clusters and their chronological exclusivity in each of these areas.

Conclusion

Our simulations reveal that the strength of cultural boundaries emerges as a significant factor influencing the Z values, and that the values obtained for our Gravettian datasets do not conform with the expectation that Isolation by Distance represents the main driver of the observed pattern.

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