Identifying Social Interaction Outliers with the Use of Network Analysis: Disk Decoration in the Middle Magdalenian Period

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Abstract. Understanding human interactions among groups located in different geographic areas is a central topic in social network analysis (SNA). In archaeological studies, where interactions must be inferred from a limited number of artifacts, this becomes particularly challenging. In this work, we introduce an SNA approach to investigate social interactions among groups from various geographic locations, focusing specifically on artifacts from the Middle Magdalenian period (ca. 15,500 to 13,000 years ago) of the Upper Paleolithic in Western Europe. The analysis considers decorative motifs on artifacts and their geographic origins to identify interaction anomalies that deserve further archaeological analysis. Two approaches are introduced: one compares the proportional deviation (absolute difference in normalized weights) from geographic relationships, and the other uses closeness and betweenness centrality. This work highlights the potential of SNA methodologies in revealing latent patterns in archaeological data and advancing the study of symbolic behavior in prehistoric societies.

Keywords: Middle Magdalenian, Perforated disks, Decorations, Symbolic behavior, Social Network Analysis, Centrality, Closeness, Betweenness

1 Introduction

The application of SNA to archaeology offers an effective and structured approach to represent the sparse and indirect datasets typical of the field. By modeling plausible interaction pathways among ancient communities, SNA enables researchers to move beyond static site descriptions toward dynamic interpretations of past social structures and regional interaction dynamics. Knappett et al. (2008), for example, used network models to study Minoan ceramics in the Aegean Bronze Age, revealing trade routes and social clustering through measures like network centrality and density [1]. Centrality metrics in particular–especially degree and betweenness–can help clarify the roles of sites as hubs or brokers within ancient trade or communication networks, which allows hypotheses about social influence and exchange to be tested [2].

Despite valuable insights from past archaeological SNA studies, symbolic and geographic data are often analyzed separately, with limited focus on how spatial proximity aligns with cultural similarity. Most analyses prioritize material distribution or abstract models, rarely linking spatial relationships to symbolic expressions. Centrality metrics are also commonly interpreted without motif context, making it difficult to determine whether observed patterns reflect intentional cultural connectivity or geographic coincidence.

Our study bridges this gap by using the correlation of geographic distance and motif (dis)similarities. We use betweenness and closeness centrality to explore whether geographic proximity aligns with symbolic motif similarity in Middle Magdalenian perforated disks whose face(s) feature one or more of a suite of decoration types.

This paper is organized as follows: Section II reviews related work in archaeological applications of SNA. Section III outlines the research objectives and presents the graph-based methodology. Section IV describes the dataset and symbolic artifacts and presents the experimental results. Section V discusses the implications of the findings, interprets notable patterns, and concludes the study.

2 Related Work

SNA can serve as a powerful analytical framework in archaeology, enabling researchers to reconstruct and interpret the structure of past human interactions through formal network metrics. Unlike traditional archaeological methods that often focus on individual sites or artifact typologies, SNA emphasizes the relational patterns that connect actors, artifacts, and places across space and time.

Mills [3] offers a foundational overview of SNA's theoretical integration into archaeological research, framing it within the paradigm of relational archaeology. The approach prioritizes interconnectivity over isolated attributes, making it especially suitable for examining complex social processes such as trade, cultural transmission, and mobility.

Similar to online social network (OSN) analysis [4], graph stream analysis [5], and unsupervised learning, applications of SNA to material distribution networks have demonstrated SNA's utility in identifying interaction hubs and shifts in regional connectivity. Sakahira et al. [6] analyze obsidian distribution during Japan's Jomon period using clustering and centrality measures to track evolving trade routes. Their work highlights how shifts in betweenness centrality values point to changes in the roles of key sites over time. Maritime archaeology has also incorporated SNA techniques to reinterpret underwater assemblages and their broader socio-economic significance. Aragon [7] integrates spatial and symbolic datasets into a network model, demonstrating how betweenness centrality can expose sites that acted as intermediaries in maritime exchange systems.

Closeness centrality has proven valuable for identifying sites with strategic access to others across the network, facilitating efficient information or material flow. Brughmans and Peeples [8] examine the application of centrality-based approaches in archaeological networks, stressing the importance of contextualizing such metrics rather than interpreting them in isolation. Similarly, Knappett et al. [1] apply closeness and degree centrality to model the spatial distribution of Minoan ceramics, revealing embedded hierarchies in trade and cultural diffusion.

In addition to empirical applications, the theoretical integration of SNA with other frameworks has expanded the interpretive potential of network-based studies. Dawson [9] advocates for such a multidimensional perspective, where network structure is analyzed alongside economic and ideological factors shaping interaction networks. Iyer et al. [10] build a model from online social networks to account for how homophily and social rank affect the formation of connections in social science.

Overall, these studies illustrate the analytical flexibility of SNA in archaeology. Metrics like betweenness and closeness centrality not only quantify structural roles of sites but also help identify unique cultural transmission, symbolic boundaries, and social organization—especially when combined with spatial and typological datasets.

3 Research Objectives and Methodology

This study approaches the relationship between spatial proximity and symbolic similarity as a problem of comparing two weighted network models derived from archaeological data. Rather than treating geographic and cultural datasets as isolated domains, we apply graph-based formalism to model and analyze structural patterns using SNA. The objective is to assess to what extent the symbolic relationships inferred from motif similarity reflect or diverge from the spatial structure encoded in site locations. Two undirected weighted graphs are constructed: a spatial network (G_s) based on linear geographic distances between Middle Magdalenian archaeological sites, and a symbolic network (G_m) based on pairwise motif similarity scores extracted from decorated disk artifacts. The shared node set V corresponds to archaeological sites, while the edge sets E_s and E_m differ in weighting semantics. Edge weights in G_s are inversely proportional to Euclidean distances between sites, representing geographic closeness. In contrast, edge weights in G_m reflect Jaccard similarity between encoded motif features, representing symbolic alignment.

To explore structural differences and commonalities between G_s and G_m, we compute closeness centrality and betweenness centrality for each node in both networks. Closeness centrality identifies nodes that are structurally central based on their average distance to all others, which is useful for assessing symbolic or spatial accessibility. Betweenness centrality, which quantifies the number of shortest paths passing through a node, highlights potential brokers or mediators in symbolic transmission or geographic flow.

These node-level centrality profiles are analyzed comparatively to assess alignment between the two networks. Specifically, we evaluate whether sites that are central in the spatial network are also central in the symbolic network—an indicator of spatial-symbolic correspondence. Additionally, we calculate edge-level differences between the two graphs to capture local deviations in pairwise relationships.

This dual-network framework enables both micro-level (edge) and macro-level (node centrality) comparison, providing a structured approach for quantifying how spatial positioning influences—or fails to influence—symbolic relationships. Such a framework not only supports hypothesis testing in an archaeological context but also contributes to broader methodological discussions of multilayer network analysis, graph comparison, and centrality-driven interpretation in the SNA community.

4 Dataset and Experimental Results

The dataset of symbolic artifacts from Middle Magdalenian (ca. 15,500-13,000 years ago) Upper Paleolithic archaeological sites across Western Europe used in this study is derived from a curated archive developed by Schwendler [11]. It includes 524 decorated disk faces from 262 artifacts, each linked to a known site with geographic coordinates. Symbolic features such as edge notching and specific engraved motifs were systematically coded as present or absent, enabling analysis of inter-site similarity of decorations. For the purposes of this study, we focus on a subset of 16 sites whose disk faces show clear symbolic motifs and that capture a mix of short-range (i.e., geographically close) and long-range interactions across the dataset. From these 16 sites come 451 decorated disk faces, which serve as the nodes in our network, resulting in a total of 202,051 possible pairwise connections or edges. The dual availability of motif-based and spatial data makes this dataset highly suited for SNA-driven exploration of symbolic and geographic interaction patterns, as it allows us to leverage two distinct types of information to test and verify our hypotheses.

To investigate the relationship between spatial proximity and symbolic similarity, we employed two complementary methods. Each method constructs and compares graph representations of the same site network, differing in how node importance and alignment are measured.

4.1 Method 1: Pairwise Edge Difference via Similarity Scores

In the first approach, we built two weighted undirected graphs sharing the same node set (archaeological sites): one where edge weights are computed as the inverse of Euclidean distances between sites (spatial graph), and another where edge weights reflect normalized Jaccard similarity scores of disk motifs (symbolic graph). To assess how well symbolic relationships reflect geographic proximity, we computed the absolute difference between corresponding edge weights in the two graphs for each site pair.

This edge-level analysis provided a matrix of difference values, quantifying the alignment of symbolic similarity with spatial closeness. However, the results revealed high divergence across most site pairs, with over 60% of edges showing differences greater than 0.6. Although some local clusters showed strong correspondence (e.g., Enlène and Lourdes), symbolic motifs often diverged sharply from geographic expectations. Crucially, this method is limited by its focus on individual pairwise relationships—it fails to detect global structural roles or identify outlier sites that are symbolically central yet geographically peripheral (or vice versa). As such, it lacks the interpretive power needed to explain cultural transmission patterns or symbolic brokerage roles.

4.2 Method 2: Node-Level Comparison via Centrality Metrics

To overcome the limitations of pairwise edge-level comparisons, the second method adopts a node-level perspective by computing and comparing two widely used centrality measures—*betweenness centrality and closeness centrality*—across the spatial and symbolic networks. These metrics allow us to assess the structural prominence of each archaeological site within its respective network, thereby enabling a deeper analysis of symbolic and spatial roles.

Centrality measures betweenness (B) and closeness (C) capture distinct structural roles within networks. Betweenness centrality quantifies how often a node lies on shortest paths between others, identifying sites that act as mediators or brokers. Closeness centrality reflects how efficiently a node can reach all others, indicating overall accessibility. Figure 1 shows normalized betweenness scores in the symbolic (left) and spatial (right) networks for the 16 sites included in this analysis. Distinct patterns emerge: *Bedeilhac* is highly central symbolically but peripheral geographically, whereas *Enlène* and *Lortet* are the reverse—geographically central but symbolically marginal. Closeness results reinforce this trend, with the site of *Kesslerloch* showing symbolic importance but low spatial integration.

Table 1 presents a numerical comparison of B_m, B_s, and Δ_B, along with C_m, C_s, and Δ_C, for the seven sites with the highest values in either metric, selected from the original analysis of 16 sites. The sites of *Bedeilhac*, *Lortet*, and *Kesslerloch* exhibit the strongest divergence, reinforcing their roles as domain-specific hubs. In contrast, *La Madeleine* and *Chancelade* maintain balanced centrality across both networks. These results underscore the structural mismatch between spatial and symbolic influence and highlight the value of dual centrality metrics for identifying culturally significant outliers. Figure 2 visualizes these differences, again showing *Bedeilhac*, *Lortet*, and *Kesslerloch* as structurally divergent, while *La Madeleine* and *Chancelade* remain consistently central across both domains.

These qualitative findings suggest that centrality-based analysis offers a more robust and interpretable framework than pairwise similarity alone. Future work will include quantitative analyses—such as correlation analysis—to evaluate the statistical significance of these observed divergences. Both closeness and betweenness centrality reveal meaningful mismatches in site roles, helping to identify outlier communities and potentially long-distance symbolic brokers. This approach underscores the decoupling of physical proximity from symbolic influence and offers a model for more nuanced, structural analysis in archaeological SNA.

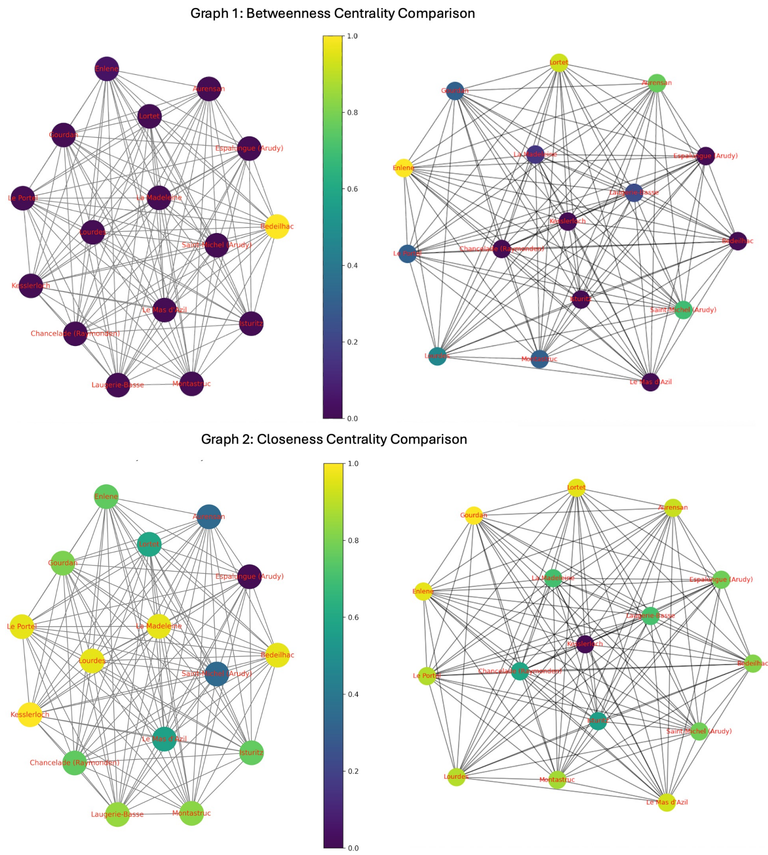

Fig. 1. Betweenness and closeness centrality comparisons. Left: symbolic similarity graph B_m. Right: spatial proximity graph B_s. Node colors indicate normalized centrality values.

Archaeological Interpretation of Outlier Sites: From an archaeological perspective, sites that show high centrality in the symbolic network but low centrality in the spatial network—such as *Bedeilhac*—may represent instances of long-distance cultural transmission. These outlier sites likely reflect groups or individuals who traveled across large geographic areas, carrying symbolic traditions with them. The motifs observed at these sites appear distinctive within their immediate region but align closely with motifs used in more distant areas, suggesting a movement of people or ideas rather than localized motif evolution. This pattern highlights the role of mobile hunter-gatherer groups in disseminating symbolic practices, and supports models of interaction that emphasize connectivity beyond immediate geographic neighbors.

Table 1. Betweenness and closeness centrality comparison between spatial and symbolic graphs, B_s, B_m, and $\Delta_B \triangleq B_s - B_m$, C_s, C_m, and $\Delta_C = C_s - C_m$

Site	B_s	B_m	Δ_B	C_s	C_m	Δ_C
Bedeilhac	0.08	1.00	-0.92	0.62	0.24	0.38
Enlène	1.00	0.08	0.92	0.71	0.69	0.02
Lortet	0.96	0.10	0.86	0.73	0.40	0.33
Kesslerloch	0.16	0.10	0.06	0.09	0.98	-0.89
La Madeleine	0.36	0.29	0.07	0.76	0.73	0.03
Lourdes	0.41	0.22	0.19	0.70	0.74	-0.04
Chancelade	0.05	0.06	-0.01	0.63	0.64	-0.01

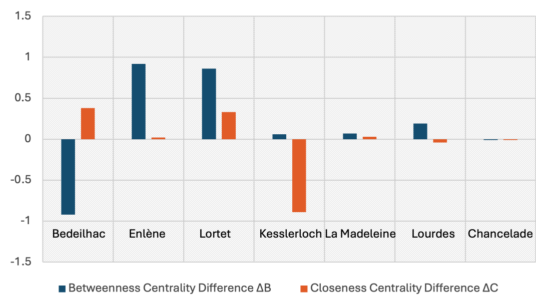

Fig. 2. Δ values of closeness and betweenness centrality in symbolic and spatial networks.

5 Conclusion

This study applied a comparative SNA framework to evaluate the relationship between geographic proximity and symbolic similarity among Middle Magdalenian perforated disk artifacts. By constructing dual networks—one based on spatial distance and the other on motif similarity—we systematically analyzed structural alignment using centrality metrics and edge-level comparisons.

Our results show that symbolic relationships do not consistently mirror spatial proximity. Pairwise similarity comparisons revealed limited overlap between geographic closeness and motif alignment, and were ineffective in isolating structurally significant sites. In contrast, centrality-based analysis provided deeper insight into site roles. Notably, the sites of *Bedeilhac*, *Lortet*, and *Kesslerloch* exhibited high divergence across both closeness and betweenness centrality, highlighting symbolic prominence that is decoupled from geographic centrality. Conversely, the sites of *La Madeleine* and *Chancelade* showed consistent structural roles in both networks, suggesting integrated participation in both spatial and symbolic spheres.

These findings underscore the value of centrality-driven SNA methods for disentangling spatial and cultural dimensions of prehistoric connectivity. By identifying mismatches between geographic and symbolic structures, our approach contributes to a more nuanced understanding of social organization, cultural transmission, and symbolic communication in Upper Paleolithic Europe. Our approach is also applicable to other geographically anchored archaeological artifacts that exhibit variation in decoration and/or form, offering a generalizable framework for exploring complex interaction patterns across multiple dimensions.

Future work could extend the model discussed here by incorporating temporal variation or cultural factors such as material sourcing or disk size, and also considering the full dataset of Middle Magdalenian disk faces.

Acknowledgment

This work was partially supported by NSF Grant SBE 2051541.

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