

The coevolution of language and art in prehistoric cave sites

Sung Do Kim^{*1} and Seungjoon Cho²

^{*}Corresponding Author: dodo@korea.ac.kr

¹Department of Linguistics, Korea University, Seoul, Republic of Korea

²Department of Linguistics, Korea University, Seoul, Republic of Korea

This paper examines arguments for the coevolution of language and art through studies on prehistoric cave sites and outlines an experimental semiotic model that recreates communication under cave-like constraints. Drawing insights from archaeoacoustics, which report correlations between prehistoric art and acoustic hotspots, cave art is read as the externalization of symbolic thought and as evidence to the multimodality of language. Cave art is not just embedded in musical and ritual performance, but it is also argued to be communally produced, making caves media of communication and situated learning. The study estimates chamber capacity from eight spaces in three caves (Lascaux, Chauvet, Altamira), yielding an average capacity of 23.5–47.7 people. Building on these estimates, we propose a virtual reality experimental semiotics model with 24 participants that manipulates communication across rounds and evaluates the use of acoustic hotspots, organization of imagery, and transmission. It is predicted that enriched vocal-gestural-musical conditions will yield focus on acoustically salient areas, more structured compositions, and higher copying accuracy, challenging the view that language leaves no material trace.

1. Introduction

The complexity of language has long been recognized (Knight et al., 1995; Kretzschmar, Jr, 2015; Bleahu, 2021; Picazo, 2021; Lund et al., 2022; Scerri & Will, 2023). It is simultaneously physical, biological, cultural, socio-political, and it is enacted in artistic behavior (Darwin, 1871; Saussure, 1916; Sapir, 1927; White, 1940; Thom, 1972, 1980, 1988; Deacon, 1997; Tomasello et al., 2005; Christiansen & Chater, 2009; Fitch, 2010; Arbib, 2018; Cuffari & Figueiredo, 2025). However, despite the broad agreement that a symbolic or cognitive revolution arose between 100,000 and 50,000 years ago (Knight et al., 1995; Harari, 2014; Scerri & Will, 2023; MacDonald et al., 2024; Zaidner et al., 2025), these other complex properties remain insufficiently understood. In particular, the co-emergence of language and art still lacks attention. To address this gap, the researchers visited 15 prehistoric cave sites across Northern Spain and Southern

France, including exterior onsite observations at Altamira, Lascaux, and Chauvet. Based on these field insights, this study aims to reveal how language and art coevolved by using experimental semiotics to recreate communicative interaction under similar constraints to prehistoric cave sites.

2. Clues from prehistoric art on the emergence and evolution of language

2.1. Cave sites provide the environmental condition for the co-emergence of language and art

Archaeoacoustics has reported strong links between prehistoric art and cave acoustics, including studies on Paleolithic and post-Paleolithic caves (Reznikoff, 1987; Waller, 1993; Dauvois, 1996; Till, 2014; Alvarez-Morales et al., 2023a, 2023b, 2023c; López-Mochales et al., 2023; Santos da Rosa et al., 2023). The concentration of paintings in the innermost chambers of caves can therefore be explained by the presence of acoustic hotspots (Blessner & Salter, 2009; Rainio et al., 2014; Mattioli et al., 2017; Miyagawa et al., 2018). To quote Waller (1993), “the images of horses, bulls, bison and deer are found in regions with high levels of sound reflection” (p. 501). Even so, results vary by site, and some studies report that links between art and acoustics are minimal or entirely absent (Fazenda et al., 2017; Santos da Rosa et al., 2025). Nevertheless, correlations between art and acoustics can be seen as clues to speech, since temperature and density, ground surface, and obstacles within these hotspots alter signal properties (Gomes et al., 2021; Pandit et al., 2022; Brandt et al., 2023). In this light, chambers with prehistoric art may have guided choices of acoustic strategies by constraining signal modulation.

2.2. Prehistoric art provides clues for the emergence of symbolic thought

Reports from archaeoacoustics align with the insight of Leroi-Gourhan (1964) that prehistoric visual expression can be read as the externalization and material symbolization of symbolic thought. Humans are often distinguished from other creatures by a uniquely symbolic mode of cognition (Deacon, 1997, 2012; Tattersall, 2017)—as Cassirer (1944) noted, we are not rational animals but symbolic ones. If early human symbolic thought surfaced in prehistoric cave art, we need a closer study of when and how such art emerged and how it correlates with language development. Of course, symbolic reference cannot be exclusively seen as the deciding factor in language evolution, since animal cognition research suggests that symbolic richness may appear in animals as well (Zuberbühler et al., 1999; Hauser, 2001; Spelke, 2003; Carruthers, 2006; Hurford, 2007; Carey, 2009).

2.3. Prehistoric art provides clues for the multimodality of language

Another important aspect of prehistoric cave art is that it is linked to the spoken language shared by members of the community. Given that these visual signs were created by communities of artists rather than solitary figures, these small groups likely used spoken language to coordinate their efforts. Such interaction is consistent with collaborative task studies showing that people use spoken descriptions to ensure a partner carries out the intended action (Clark & Wilkes-Gibbs, 1986), and that verbal instruction improves coordination and group performance in cooperative tasks (Xie et al., 2023; Yin et al., 2025). Miyagawa et al. (2018) also define cave art as an example of cross-modal information transfer in which auditory signals are converted into visual representations. Here, cross-modal information transfer is defined as the process where external auditory triggers—such as thunder, rock tapping, or music—are mentally transformed into visual art. Building from this perspective, art can even be viewed as a form of language (Ochoa & García-Diez, 2018). Anati (2004) argues that Paleolithic rock art forms a decipherable visual grammar, a cross-culturally recurrent system of signs. Recent large-scale compilations of cave art also show placement rules. Specific motifs recur with certain zones, indicating location-conditioned combinatoriality (Intxaurbe et al., 2024). Even early prehistoric art in southern Africa—engraved ochres and pierced shells at Blombos (Henshilwood et al., 2018; d’Errico et al., 2023)—can function as a quasi-fossil record of human language in the modern sense. Many scholars have further argued that rituals may have taken place at cave art sites (Clottes, 1999, 2013; Barzilai et al., 2024). This is supported by studies on commonalities between art and dance, one example of which is the concept of the line. Considering the kinesthetic responses lines elicit in the body (Ingold, 2015), contemporary artistic practice can discover similarities with petroglyphs (Tilley & Bennett, 2008). It can therefore be suggested that cave sites were not occupied solely by artists, but also by spectators and musical performers. In this context, prehistoric art is best understood not as monosemiotic but as polysemiotic, insofar as it combines distinct semiotic systems (Zlatev et al., 2023).

2.4. Prehistoric art provides clues for the transmission of language and situated learning

As previously mentioned, identifying artists shows cave imagery as the work of communities, not solitary creators. Finger-fluting, in this view, shows prehistoric art was communal. Research shows that children and adults, women and men, fluted together at Rouffignac, Gargas, Las Chimeneas, and El Castillo. Many

Rouffignac mammoths point to apprenticeship within a community of practice (Lave & Wenger, 1991; Lave, 1996; Handley et al., 2006). Cave imagery was therefore a medium of communication—a tool for transmitting rules, relations, and beliefs (Geertz, 1976; Jochim, 1982; Hewlett & Cavalli-Sforza, 1986; Rowlands, 1992; Conkey, 2001; Garate et al., 2023; Garate, 2025; Wisher & Palacio-Pérez, 2025). This aligns again with Leroi-Gourhan's concept of the mythogram, which ties memory to myth and ritual, accessed in ceremonial contexts (Jones, 2007; Porr, 2010; Zubieta, 2022; Ramírez Galicia, 2024). However, it is also important to note that, if these decorated caves held deep ritual significance, the accessibility to these sites may have been restricted to specific individuals or initiated groups (Guy, 2017; Spaey et al., 2024). Consequently, our reference to communal activity should be understood as socially bounded participation—a shared and transmitted practice, but one that may have occurred within strictly regulated, ritualistic contexts.

3. Experimental semiotic approach to the coevolution of language and art

3.1. Why experimental semiotics?

In the following section, we intend to propose an experiment which tests how acoustic conditions shape (i) the preferential use of the acoustic hotspot, (ii) the internal organization of the imagery, and (iii) transmission from producers to spectators. To structure this investigation, we draw upon experimental semiotics, which studies how people create new communication systems, focusing on interaction without pre-established conventions—rather than studying mature languages (Galantucci & Garrod, 2011; Galantucci et al., 2012; Inoue & Morita, 2021; Delliponti et al., 2023; Okumura et al., 2023). For example, silent-gesture experiments have been used to explore the origins of grammatical structures (Goldin-Meadow et al., 2008; Schouwstra & de Swart, 2014; Culbertson et al., 2020; Ortega et al., 2020). Sign language has drawn particular attention because natural sign languages exhibit evolutionary stages similar to those seen in gesture systems that were made in the laboratory (Senghas et al., 2004; Fusellier-Souza, 2006; Motamedi et al., 2019; Moita et al., 2023; Flaherty & Schouwstra, 2025). Additionally, iterative learning research allows us to observe how the system evolves over time (Kirby et al., 2014). However, experimental semiotics is often faulted for low ecological validity because tasks are highly abstract or artificial (Tamariz 2017; Nölle & Peeters, 2025). It has been proposed that the use of virtual reality can balance this trade-off by combining experimental control with ecological plausibility, grounding tasks in realistic, multimodal settings (Galantucci et al. 2012; Nölle & Galantucci 2022; Nölle & Peeters, 2025).

3.2. Chamber capacity and number of participants

To determine a valid group size for testing the co-evolution of cave art and language, we estimated the occupancy of eight decorated chambers across Lascaux, Chauvet, and Altamira. Usable floor space was calculated by discounting plan areas for physical constraints, then divided by posture-dependent allowances ranging from 1.3 to 4.5 m² per person, yielding an average capacity estimate of approximately 23.5 to 47.7 people. However, as this analysis represents a speculative and preliminary estimate of prehistoric cave capacities, the selection of 24 participants serves merely as an illustrative example for our proposed experimental design.

3.3. Proposed task

If we assume that roughly 24 people participated in the production process of cave paintings, a key remaining question is how their roles would have been allocated. The classification of participants' roles and the setting of participant numbers draw on archaeologist Garate's cost-calculation model, which estimates the minimum human labor cost invested in producing cave art (Garate, 2025). First, the acoustic conditions of the cave and its interior chambers constrain and guide how utterances and sounds are used, and within these constraints (a) a suitable location is selected through reconnaissance of cave positions. At that location, spoken language is visualized and conversely, prehistoric art can also be verbalized. Therefore, visual language requires (b) a provider of directives indicating what to draw, where, and how; (c) an evaluator who checks the progress of production and makes corrections; and (d) performers of music and hoofbeat sounds. As for the technical skills required for visual art, tasks such as (e) mural production, (f) assistance with lighting, and (g) pigment preparation would be differentiated and carried out separately. This entire process constitutes a single act of communication, and if we consider that children also participated in cave-painting production processes such as finger fluting, it will be assumed that, of the 24 participants, 12 learned the techniques as viewers. (Figure 1.)

We propose a virtual reality experiment, since virtual reality allows the 24 participants to act in interactive, multimodal 3D worlds while researchers manipulate one variable at a time. A desktop cave scene renders irregular paintable walls and spatialized audio with a pre-registered hotspot where sound is louder and more reverberant, while non-hotspot areas are muffled. Participants are not told about this difference. They enter the virtual cave with keyboard and mouse, after listening to a soundscape of hoof impacts, bird songs, and environmental noise. Communication is manipulated across three rounds: (A)

-muted microphone only allowing gesture; (B) restricted speech plus gesture; and (C) unrestricted speech plus gesture, hoofbeat imitation, and simple music. Each round has a producer group and a spectator group. A producer group first creates visual panels on irregular wall surfaces; a spectator group later attempts to create similar panels under the same communicative constraints.

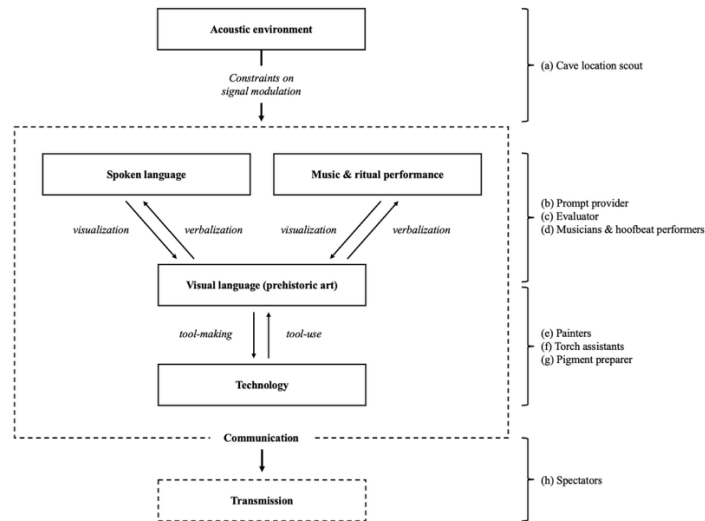


Figure 1. Coevolution model for round (C).

We predict that the enriched vocal–gestural–musical condition (C) will yield tighter spatial focus on acoustically salient areas, more structured panel compositions, and higher copying accuracy than (B), with the most constrained condition (A) producing the weakest spatial targeting, least organized panels, and lowest transmission fidelity.

4. Conclusion

Prehistoric art, long treated as a separate domain, should be re-evaluated as a critical quasi-fossil record of language evolution. The assumption that language leaves no trace is challenged by reports that show Paleolithic art was in fact a dynamic, multimodal, and environmentally situated communicative practice. The strong correlation between cave art and acoustic hotspots points to a system of externalized symbolic thought, linked with spoken and musical forms of expression. To test these arguments, we propose a novel experimental semiotics model that demonstrates this coevolution of language and art within a controlled, cave-like environment enabled by virtual reality technology.

Acknowledgements

This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2025S1A5B1008242).

References

- Álvarez-Morales, L., Santos da Rosa, N., Benítez-Aragón, D., Lazarich, M., y Díaz-Andreu, M. (2023). Acústica de recintos prehistóricos: estudio arqueoacústico de Palomas I. In *54º Congreso Español de Acústica - Tecniacústica 2023*.
- Alvarez-Morales, L., Santos da Rosa, N., Benítez-Aragón, D., Lazarich, M., & Díaz-Andreu, M. (2023). Recovering the intangible acoustic heritage of rock art sites: El Tajo de las Figuras as a case study. *2023 Immersive and 3D Audio: from Architecture to Automotive (I3DA)*, 1-7.
- Alvarez-Morales, L., Santos da Rosa, N., Benítez-Aragón, D., Fernández Macías, L., Lazarich, M., & Díaz-Andreu, M. (2023). The Bacinete main shelter: a Prehistoric theatre?. *Acoustics*, 5(1). MDPI.
- Anati, E., & Laurant, S. (2004). Grammaire de la préhistoire. *Revue Des Deux Mondes*, 89–94. <http://www.jstor.org/stable/44191351>
- Arbib, M. A. (2018). Computational challenges of evolving the language-ready brain: 1. From manual action to protosign. *Interaction Studies*, 19(1–2), 7–21. <https://doi.org/10.1075/is.17036.arb>
- Barzilai, O., Marder, O., Tejero, J. M., Ayalon, A., Bar-Matthews, M., Abulafia, T., Lavi, R., Goder-Goldberger, M., Shemer, M., Edeltin, L., Wiegmann, A., Frumkin, A., Karasik, A., Yasur, G., Yeshurun, R., Zohar, I., Berna, F., Hans, M., Goldberg, J. S., McDermott, Y., ... HersHKovitz, I. (2024). Early human collective practices and symbolism in the Early Upper Paleolithic of Southwest Asia. *Proceedings of the National Academy of Sciences of the United States of America*, 121(51), e2404632121. <https://doi.org/10.1073/pnas.2404632121>
- Bleahu, A. (2021). The human symbolic revolution: An Uexküllian perspective. *Hortus semioticus*, 8, 73-86.
- Blessner, B., & Salter, L.-R. (2009). *Spaces speak, are you listening?* MIT Press.
- Brandt, E. E., Duke, S., Wang, H., & Mhatre, N. (2023). The ground offers acoustic efficiency gains for crickets and other calling animals. *Proceedings of the National Academy of Sciences*, 120, e2302814120.
- Brumm, H., & Slabbekoorn, H. (2005). Acoustic communication in noise. *Advances in the Study of Behavior*, 35, 151–209. [https://doi.org/10.1016/S0065-3454\(05\)35004-2](https://doi.org/10.1016/S0065-3454(05)35004-2)
- Carey, S. (2009). *The origin of concepts*. Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780195367638.001.0001>
- Carruthers, P. (2006). *The architecture of the mind*. Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780199207077.001.0001>

- Cassirer, E. (1944). *An essay on man; an introduction to a philosophy of human culture*. Yale University Press.
- Christiansen, M. H., & Chater, N. (2009). The biological and cultural foundations of language. *Communicative & Integrative Biology*, 2(3), 221–222. <https://doi.org/10.4161/cib.2.3.8034>
- Clark, H. H., & Wilkes-Gibbs, D. (1986). Referring as a collaborative process. *Cognition*, 22(1), 1–39.
- Clink, D. J., Hamid Ahmad, A., & Klinck, H. (2020). Gibbons aren't singing in the rain: Presence and amount of rainfall influences ape calling behavior in Sabah, Malaysia. *Scientific Reports*, 10, 1282.
- Clottes, J. (1999). Twenty thousand years of Palaeolithic cave art in Southern France. In J. Clottes (Ed.), *World Prehistory: Studies in Memory of Grahame Clark* (pp. 161–175).
- Clottes, J. (2013). Consequences of the discovery and study of the Chauvet Cave. In K. Sachs-Hombach & J. R. J. Schirra (Eds.), *Origins of pictures* (pp. 46–71). Herbert von Halem.
- Conkey, M. (2001). Hunting for images, gathering up meanings: Art for life in hunting-gathering societies. In C. Panter-Brick, R. H. Layton, & P. Rowley-Conwy (Eds.), *Hunter-gatherers: An interdisciplinary perspective* (pp. 267–291). Cambridge University Press.
- Cuffari, E. C., & Figueiredo, N. M. (2025). Intentions in interactions: An enactive response to expressive communication proposals. *Synthese*, 205, 46.
- Culbertson, J., Franck, J., Braquet, G., Navarro, M. B., & Arnon, I. (2020). A learning bias for word order harmony: Evidence from speakers of non-harmonic languages. *Cognition*, 204, Article 104392. <https://doi.org/10.1016/j.cognition.2020.104392>
- d'Errico, F., van Niekerk, K. L., Geis, L., & Henshilwood, C. S. (2023). New Blombos Cave evidence supports a multistep evolutionary scenario for the culturalization of the human body. *Journal of human evolution*, 184, 103438. <https://doi.org/10.1016/j.jhevol.2023.103438>
- Darwin, C. (1871). *The descent of man, and selection in relation to sex*. John Murray.
- Dauvois, M. (1996). Evidence of sound-making and the acoustic character of the decorated caves of the Western Paleolithic world. *International Newsletter on Rock Art*, 13, 23–25.
- Deacon, T. W. (1997). *The symbolic species: The co-evolution of language and the brain*. W. W. Norton & Company.
- Deacon, T. W. (2012). *Incomplete nature: How mind emerged from matter*. W. W. Norton & Company.
- Delliponti, A., Raia, R., Sanguedolce, G., Gutowski, A., Pleyer, M., Sibierska, M., Placiński, M., Żywicznyński, P., & Waciewicz, S. (2022). Experimental Semiotics: A Systematic Categorization of Experimental Studies on the

- Bootstrapping of Communication Systems. *Biosemiotics*, 16, 291–310.
<https://doi.org/10.1007/s12304-023-09534-x>
- Fazenda, B., Scarre, C., Till, R., Pasalodos, R. J., Guerra, M. R., Tejedor, C., et al. (2017). Cave acoustics in prehistory: Exploring the association of Palaeolithic visual motifs and acoustic response. *Journal of the Acoustical Society of America*, 142, 1332. <https://doi.org/10.1121/1.4998721>
- Fitch, W. T. (2010). *The evolution of language*. Cambridge University Press.
<https://doi.org/10.1017/CBO9780511817779>
- Flaherty, M., & Schouwstra, M. (2025). Validating Silent Gesture Lab Studies in a Naturally Emerging Sign Language: How Order is Used to Describe Intensional Versus Extensional Events in Nicaraguan Sign Language. *Topics in Cognitive Science*, 17(3), 609–624.
- Fusellier-Souza, I. (2006). Emergence and development of signed languages: From a semiogenetic point of view. *Sign Language Studies*, 7(1), 30–56.
<https://doi.org/10.1353/sls.2006.0030>
- Galantucci, B. (2005). An experimental study of the emergence of human communication systems. *Cognitive Science*, 29(5), 737–767.
https://doi.org/10.1207/s15516709cog0000_34
- Galantucci, B., & Garrod, S. (2011). Experimental semiotics: a review. *Frontiers in human neuroscience*, 5(11). <https://doi.org/10.3389/fnhum.2011.00011>
- Galantucci, B., Garrod, S., & Roberts, G. (2012). Experimental semiotics. *Language and Linguistics Compass*, 6(8), 477–493.
<https://doi.org/10.1002/lnc3.351>
- Garate, D. (2025). The Role of Palaeolithic Cave-Art: Estimating Social Investment in Symbolic Expressions Through the Making Cost. *Journal of Archaeological Method and Theory*, 32(2), 1–27.
- Garate, D., Rivero, O., Rios-Garaizar, J., Medina-Alcaide, M. Á., Arriolabengoa, M., Intxaurbe, I., ... & Salazar, S. (2023). Unravelling the skills and motivations of Magdalenian artists in the depths of Atxurra Cave (Northern Spain). *Scientific Reports*, 13(1), 17340.
- Garrod, S., Fay, N., Lee, J., Oberlander, J., & MacLeod, T. (2007). Foundations of representation: Where might graphical symbol systems come from? *Cognitive Science*, 31(6), 961–987.
<https://doi.org/10.1080/03640210701703659>
- Geertz, C. (1976). Art as a cultural system. *Modern Language Notes*, 91, 1473–1499.
- Goldin-Meadow, S., So, W. C., Özyürek, A., & Mylander, C. (2008). The natural order of events: How speakers of different languages represent events nonverbally. *Proceedings of the National Academy of Sciences*, 105(27), 9163–9168. <https://doi.org/10.1073/pnas.0710060105>
- Gomes, D. G. E., Toth, C. A., Cole, H. J., Francis, C. D., & Barber, J. R. (2021). Phantom rivers filter birds and bats by acoustic niche. *Nature Communications*, 12, 3029.

- Guy, E. (2017). *Ce que l'art préhistorique dit de nos origines*. Flammarion.
- Handley, K., Sturdy, A., Finch, R., & Clark, T. (2006). Within and beyond communities of practice: Making sense of learning through participation, identity and practice. *Journal of Management Studies*, 43(3), 641–653.
- Harari, Y. N. (2014). *Sapiens: A brief history of humankind*. Harper.
- Hart, P. J., Hall, R., Ray, W., Beck, A., & Zook, J. (2015). Cicadas impact bird communication in a noisy tropical rainforest. *PLoS ONE*, 10(3), e0120179.
- Hauser, M. D. (2001). *Wild minds: What animals really think*. Owl Books.
- Henshilwood, C. S., d'Errico, F., van Niekerk, K. L., Dayet, L., Queffelec, A., & Pollarolo, L. (2018). An abstract drawing from the 73,000-year-old levels at Blombos Cave, South Africa. *Nature*, 562(7725), 115–118. <https://doi.org/10.1038/s41586-018-0514-3>
- Hewlett, B. S., & Cavalli-Sforza, L. L. (1986). Cultural transmission among Aka Pygmies. *American Anthropologist*, 88(4), 922–934.
- Hurford, J. R. (2007). *The origins of meaning*. Oxford University Press.
- Ingold, T. (2015). *The Life of Lines* (1st ed.). Routledge. <https://doi.org/10.4324/9781315727240>
- Inoue, N., & Morita, J. (2021). A behavioral task for exploring dynamics of communication system in dilemma situations. *Artificial Life and Robotics*, 26(3), 329–337. <https://doi.org/10.1007/s10015-021-00680-4>
- Intxaurbe, I., Ochoa, B., & García-Díez, M. (2024). Drawing in the depths: Spatial organization patterns related to Magdalenian cave art. *Archaeological and Anthropological Sciences*. (Advance online publication).
- Jochim, M. (1982). Palaeolithic cave art in ecological perspective. In G. Bailey (Ed.), *Hunter-gatherer economy in prehistory* (pp. 212–219). Cambridge University Press.
- Jones, A. (2007). *Memory and material culture*. Cambridge University Press.
- Kirby, S., Griffiths, T., & Smith, K. (2014). Iterated learning and the evolution of language. *Current opinion in neurobiology*, 28, 108–114. <https://doi.org/10.1016/j.conb.2014.07.014>
- Knight, C., Power, C., & Watts, I. (1995). The human symbolic revolution: A Darwinian account. *Cambridge Archaeological Journal*, 5(1), 75–114. <https://doi.org/10.1017/S0959774300001190>
- Kretzschmar, W. A., Jr. (2015). *Language and complex systems*. Cambridge University Press.
- Lave, J. (1996). Teaching, as learning, in practice. *Mind, Culture, and Activity*, 3(3), 149–164.
- Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.
- Leroi-Gourhan, A. (1964). *Les religions de la préhistoire*. Presses Universitaires de France.
- López-Mochales, S., Alvarez-Morales, L., Da Rosa, N. S., Lazarich, M., Díaz-Andreu, M., & Escera, C. (2023). Psychoacoustics of rock art sites: the case

- study of the shelters Diosa I and Horadada (Cádiz, Spain). In *2023 Immersive and 3D Audio: from Architecture to Automotive (I3DA)* (pp. 1-8). IEEE.
- Lund, K., Basso Fossali, P., Mazur, A., & Ollagnier-Beldame, M. (Eds.). (2022). *Language is a complex adaptive system: Explorations and evidence*. Language Science Press.
- MacDonald, B. L., Velliky, E. C., Forrester, B., Riedesel, S., Linstädter, J., Kuo, A. L., Woodborne, S., Mabuza, A., & Bader, G. D. (2024). Ochre communities of practice in Stone Age Eswatini. *Nature communications*, 15(1), 9201. <https://doi.org/10.1038/s41467-024-53050-6>
- Mattioli, T., Farina, A., Armelloni, E., & Díaz-Andreu, M. (2017). Echoing landscapes: Echolocation and the placement of rock art in the central Mediterranean. *Journal of Archaeological Science*, 83, 12–25. <https://doi.org/10.1016/j.jas.2017.04.008>
- Memet, J.-B., Farrell, A., & Mahadevan, L. (2022). An allometric prior enhances acoustic niche partitioning. *Journal of the Royal Society Interface*, 19(197), 20220421. <https://doi.org/10.1098/rsif.2022.0421>
- Miyagawa, S., Lesure, C., & Nóbrega, V. A. (2018). Cross-modality information transfer: A hypothesis about the relationship among prehistoric cave paintings, symbolic thinking, and the emergence of language. *Frontiers in Psychology*, 9, 115. <https://doi.org/10.3389/fpsyg.2018.00115>
- Moita, M., Abreu, A. M., & Mineiro, A. (2023). Iconicity in the emergence of a phonological system?. *Journal of Language Evolution*, 8(1), 1-17.
- Motamedi, Y., Little, H., Nielsen, A., & Sulik, J. (2019). The iconicity toolbox: Empirical approaches to measuring iconicity. *Language and Cognition*, 11(2), 188–207. <https://doi.org/10.1017/langcog.2019.14>
- Nölle, J. & Galantucci, B. (2022). Experimental semiotics: Past, present, and future. In A. M. Garcia & A. Ibanez (Eds.), *The Routledge Handbook of Semiosis and the Brain*. (pp. 66–81). New York: Routledge.
- Nölle, J. & Peeters, D. (2025). Virtual reality as a tool to study language evolution. In L. Raviv & C. Boeckx (Eds.), *The Oxford Handbook of Approaches to Language Evolution*. (pp. 63–82). Oxford University Press.
- Ochoa, B. & García-Diez, M. (2018) The use of cave art through graphic space, visibility and cave transit: A new methodology. *Journal of Anthropological Archaeology*, 49, 129–145. <https://doi.org/10.1016/j.jaa.2017.12.008>
- Okumura, R., Taniguchi, T., Hagiwara, Y., & Taniguchi, A. (2023). Metropolis-Hastings algorithm in joint-attention naming game: Experimental semiotics study. *Frontiers in artificial intelligence*, 6, 1235231. <https://doi.org/10.3389/frai.2023.1235231>
- Ortega, G., Özyürek, A., & Peeters, D. (2020). Iconic gestures serve as manual cognates in hearing second language learners of a sign language: An ERP study. *Journal of experimental psychology. Learning, memory, and cognition*, 46(3), 403–415. <https://doi.org/10.1037/xlm0000729>

- Pandit, M. M., Bridge, E. S., & Ross, J. D. (2022). Environmental conditions lead to shifts in individual communication, which can cause cascading effects on soundscape composition. *Ecology and Evolution*, 12(10), e9359.
- Peirce, C. S. (1998). *The essential Peirce: Selected philosophical writings, Volume 2 (1893–1913)* (Peirce Edition Project, Ed.). Indiana University Press.
- Picazo, G. (2021). New foundations (Natural language as a complex system, or new foundations for philosophical semantics, epistemology and metaphysics, based on the process-socio-environmental conception of linguistic meaning and knowledge). *Journal of Research in Humanities and Social Science*, 9(6), 33–44.
- Pieretti, N., Farina, A., & Morri, D. (2011). A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI). *Ecological Indicators*, 11(3), 868–873. <https://doi.org/10.1016/j.ecolind.2010.11.005>
- Porr, M. (2010). Palaeolithic art as cultural memory: A case study of the Aurignacian art of southwest Germany. *Cambridge Archaeological Journal*, 20(1), 87–108.
- Raick, X., Campisi, J., Under The Pole Consortium, Bertucci, F., Lecchini, D., Di Iorio, L., & Parmentier, E. (2025). Depth-dependent dynamics and acoustic niche partitioning of fish sounds in mesophotic coral reefs. *Estuarine, Coastal and Shelf Science*, 322, 109336. <https://doi.org/10.1016/j.ecss.2025.109336>
- Rainio, R., Lahelma, A., Äikäs, T., Lassfolk, K., & Okkonen, J. (2014). Acoustic measurements at the rock painting of värikallio, Northern Finland. In *International Multi-disciplinary Conference on The Archaeology of Sound* (pp. 141-152). The OTS Foundation.
- Ramírez Galicia, A. (2024). L'étude des sols d'habitat et des grottes ornées dans l'œuvre d'André Leroi-Gourhan: Du temps éphémère d'un campement à la très longue durée des mythes. *Artefact*, 21, 349–377. <https://journals.openedition.org/artefact/16404>
- Reed, V. A., Francis, C. D., Toth, C. A., Wardle, R. A., Gomes, D. G. E., & Barber, J. R. (2022). Experimentally broadcast ocean surf and river noise alters birdsong. *PeerJ*, 10, e13297.
- Reznikoff, I. (1987). Sur la dimension sonore des grottes peintes du paléolithique. *Comptes Rendus de l'Académie des Sciences*, 304, 153–156.
- Rowlands, M. (1992). The role of memory in the transmission of culture. *World Archaeology*, 25(2), 141–151.
- Santos da Rosa, N., Alvarez-Morales, L., Moreno-Iglesias, D., Laue, G., & Diaz-Andreu, M. (2025). On the relationship between sound, acoustics, and San rock art: An archaeoacoustic study at twenty-seven sites in the Maloti-Drakensberg mountains (South Africa). *Journal of Archaeological Science: Reports*, 61, 104900.

- Santos da Rosa, N., Morales, L. Á., Briz, X. M., Macías, L. F., & Díaz-Andreu, M. (2023). The acoustics of aggregation sites: Listening to the rock art landscape of Cuevas de la Araña (Spain). *Journal of Field Archaeology*, 48(2), 130-143.
- Sapir, E. (1927). Language as a form of human behavior. *The English Journal*, 16(6), 421-433.
- Saussure, F. (1916). *Course in General Linguistics*. London: Duckworth.
- Scerri, E. M. L., & Will, M. (2023). The revolution that still isn't: The origins of behavioral complexity in Homo sapiens. *Journal of Human Evolution*, 179, 103358. <https://doi.org/10.1016/j.jhevol.2023.103358>
- Schouwstra, M., & de Swart, H. (2014). The semantic origins of word order. *Cognition*, 131(3), 431-436. <https://doi.org/10.1016/j.cognition.2014.03.004>
- Scott-Phillips, T. C., Kirby, S., & Ritchie, G. R. (2009). Signalling signalhood and the emergence of communication. *Cognition*, 113(2), 226-233. <https://doi.org/10.1016/j.cognition.2009.08.009>
- Senghas, A., Kita, S., & Özyürek, A. (2004). Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. *Science*, 305(5691), 1779-1782. <https://doi.org/10.1126/science.1100199>
- Slabbekoorn, H. (2004). Singing in the wild: The ecology of birdsong. In P. Marler & H. Slabbekoorn (Eds.), *Nature's music: The science of birdsong* (pp. 178-205). Elsevier Academic Press.
- Slabbekoorn, H., & Peet, M. (2003). Birds sing at a higher pitch in urban noise. *Nature*, 424(6946), 267. <https://doi.org/10.1038/424267a>
- Spaey, O., Garate, D. & Irurtzun, A. (2024) Space Analysis in Palaeolithic Cave Art: Towards a Multidisciplinary and Integrated Approach. *Journal of Archaeological Method and Theory*, 31(1), 1803-1842.
- Spelke, E. (2003). What makes us smart? Core knowledge and natural language. In D. Gentner & S. Goldin-Meadow (Eds.), *Language and mind: Advances in the study of language and thought* (pp. 277-311). MIT Press.
- Tamariz, M. (2017). Experimental Studies on the Cultural Evolution of Language. *Annual Review of Linguistics*, 3, 389-407. <https://doi.org/10.1146/annurev-linguistics-011516-033807>
- Tattersall, I. (2017). Why was human evolution so rapid? In A. Marom & E. Hovers (Eds.), *Human paleontology and prehistory* (pp. 1-9). Springer.
- Thom, R. (1972). *Stabilité structurelle et morphogénèse: Essai d'une théorie générale des modèles*. W. A. Benjamin.
- Thom, R. (1980). *Modèles mathématiques de la morphogénèse*. Paris: Christian Bourgois.
- Thom, R. (1988). *Esquisse d'une sémiophysique*. Paris: InterÉditions.
- Till, R. (2014). Sound archaeology: terminology, Palaeolithic cave art and the soundscape. *World Archaeology*, 46(3), 292-304. <http://www.jstor.org/stable/26160227>

- Tilley, C. Y., & Bennett, W. (2008). *Body and image: Explorations in landscape phenomenology* 2. Left Coast Press.
- Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: The origins of cultural cognition. *Behavioral and Brain Sciences*, 28, 675–691.
- Waller, S. (1993). Sound and rock art. *Nature*, 363, 501. <https://doi.org/10.1038/363501a0>
- White, L. A. (1940). The symbol: The origin and basis of human behavior. *Philosophy of Science*, 7(4), 451–463. <https://doi.org/10.1086/286655>
- Wisher, I., & Palacio-Pérez, E. (2025). Dialogues Across Time? Conceptualising the Temporal Relationships of Palimpsests in the Upper Palaeolithic Cave Art of El Castillo (Cantabria, Spain) I. Wisher. & E. Palacio-Pérez. *Journal of Archaeological Method and Theory*, 32(3), 49.
- Wood, W. E., & Yezerinac, S. M. (2006). Song Sparrow (*Melospiza melodia*) song varies with urban noise. *The Auk*, 123(3), 650–659.
- Xie, E., Li, K., Gu, R., Zhang, D., & Li, X. (2023). Verbal information exchange enhances collective performance through increasing group identification. *NeuroImage*, 279(1), 1–12.
- Yin, Z., Xuan, B., & Zhang, M. (2025). How role reversal and interpersonal closeness shape verbal communication cooperation: An fNIRS hyperscanning study. *Brain Structure and Function*, 230(8), 1–16.
- Zaidner, Y., Prévost, M., Shahack-Gross, R., Weissbrod, L., Yeshurun, R., Porat, N., Guérin, G., Mercier, N., Galy, A., Pécheyran, C., Barbotin, G., Tribolo, C., Valladas, H., White, D., Timms, R., Blockley, S., Frumkin, A., Gaitero-Santos, D., Ilani, S., Ben-Haim, S., ... HersHKovitz, I. (2025). Evidence from TinsHemet Cave in Israel suggests behavioural uniformity across Homo groups in the Levantine mid-Middle Palaeolithic circa 130,000-80,000 years ago. *Nature human behaviour*, 9(5), 886–901. <https://doi.org/10.1038/s41562-025-02110-y>
- Zlatev, J., Devylder, S., Defina, R., Moskaluk, K. & Andersen, L. (2023). Analyzing polysemiosis: language, gesture, and depiction in two cultural practices with sand drawing. *Semiotica*, 2023(253), 81-116. <https://doi.org/10.1515/sem-2022-0102>
- Zuberbühler, K., Cheney, D. L., & Seyfarth, R. M. (1999). Conceptual semantics in a nonhuman primate. *Journal of Comparative Psychology*, 113(1), 33–42. <https://doi.org/10.1037/0735-7036.113.1.33>
- Zubieta, L. F. (2022). The Role of Rock Art as a Mnemonic Device in the Memorisation of Cultural Knowledge. *Springer International Publishing*. https://doi.org/10.1007/978-3-030-96942-4_4