Title

Meaning-Making as Symmetry-Breaking: Spectral Thermodynamics of Emergent Communication

Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 48(0)

Authors

Hallajian, Amir Homayun
Koch, Saskia
Bašnáková, Jana
et al.

Publication Date

2026

Meaning-Making as Symmetry-Breaking: Spectral Thermodynamics of Emergent Communication

Amir-Homayun Hallajian (Amirhomayun.Hallajian@donders.ru.nl)
Donders Institute for Brain, Cognition, and Behaviour, Radboud University, Nijmegen, the Netherlands

Saskia B. J. Koch (Saskia.Koch@donders.ru.nl)
Donders Institute for Brain, Cognition, and Behaviour, Radboud University, Nijmegen, the Netherlands

Jana Bašnáková (Jana.Basnakova@savba.sk)
Institute of Experimental Psychology CSPS, Slovak Academy of Sciences, Bratislava, Slovakia

Arjen Stolk (Arjen.Stolk@dartmouth.edu)*
Department of Psychological and Brain Sciences, Dartmouth College, Hanover, NH, USA

Ivan Toni (Ivan.Toni@donders.ru.nl)*
Donders Institute for Brain, Cognition, and Behaviour, Radboud University, Nijmegen, the Netherlands

*These authors contributed equally

Abstract

How do interlocutors achieve mutual understanding when communicative mappings are not given in advance? We propose that meaning-making is a symmetry-breaking constructive process: through interaction, dyads compress an open space of communicative possibilities into a low-dimensional set of shared alternatives, namely dyad-specific signal-referent relations that enable coordination. We test this account in 69 dyads using a real-time semiotic game in which participants invent and stabilize dyad-specific communicative conventions, modeling signal–referent relations with spectral graph thermodynamics. Successful dyads exhibited dimensional compression of their signaling space: intrinsic dimensionality was reduced sixfold relative to random networks, reflecting the emergence of stabilized dyad-specific conventions. These dyads also showed lower thermodynamic efficiency, indicating that constructing shared signal–referent structure carries an entropy cost. Thermodynamic and geometric measures converged at a mesoscale diffusion regime, where relational constraints operate. These findings suggest that mutual understanding depends on actively constructing a shared, low-dimensional communicative structure through interaction.

Keywords: referential communication; complex systems; spectral graph theory; experimental semiotics

Introduction

Many theories of human communication elaborate on Shannon's mathematical framework, where information is defined as the reduction in statistical uncertainty that a signal brings to a system about the state of another system (Shannon, 1948). In this view, a sender encodes mental content into a signal, the signal passes through a noisy medium, and a receiver decodes it to recover the original content. The Rational Speech Act formalizes this intuition as Bayesian updating over a hypothesis space of meanings, modeling speakers and listeners as rational agents who choose and interpret utterances against a mutually known repertoire of possibilities (Goodman & Frank, 2016). Active inference models similarly cast interlocutors as prediction-error minimizers operating within shared generative models that specify the causes of sensory signals (Friston & Frith, 2015). These frameworks share a transparency assumption: interlocutors have access to a cognitively transparent hypothesis space whose structure is fixed and known in advance.

But transparency is often precisely what communicators must create. In natural dialogue, interlocutors frequently lack pre-established codebooks. They must jointly discover which distinctions matter, which signals mark those distinctions, and how context modulates interpretation, all while interaction unfolds in real time (Clark, 1996; Stolk et al., 2016). Furthermore, interlocutors' choices depend heavily on their own interaction history: signals that are effective for insiders, who share communicative history, can be opaque to outsiders (Garrod et al., 2007). Accordingly, it has been argued that dyads stabilize not only signal-referent mappings but a historically sedimented organization that emerges through repeated joint action (Brennan & Clark, 1996). Experimental semiotics make this vivid: when dyads invent novel signals from scratch, they cannot select among shared alternatives because no such alternatives yet exist (Galantucci, 2005; Garrod et al., 2007). Even when the reference space is experimentally limited, the signaling space remains open-ended as different dyads invent different signals. The central computational problem of human referential communication, then, is not selection within a transparent space but construction of the space itself.

We propose that this constructive meaning-making process follows fundamental principles of organization characteristic of far-from-equilibrium complex systems. Disordered systems are isotropic, with many roughly equivalent microstates. When fluctuations are selectively amplified, such systems undergo bifurcation, settling into one of several possible macroscopic patterns and thereby breaking symmetry. Order crystallizes from disorder at a critical

In G. Boleda, I. Dautriche, M. Maldonado, C. Saldana and T. Torrent (Eds.), *Proceedings of the 48th Annual Conference of the Cognitive Science Society*

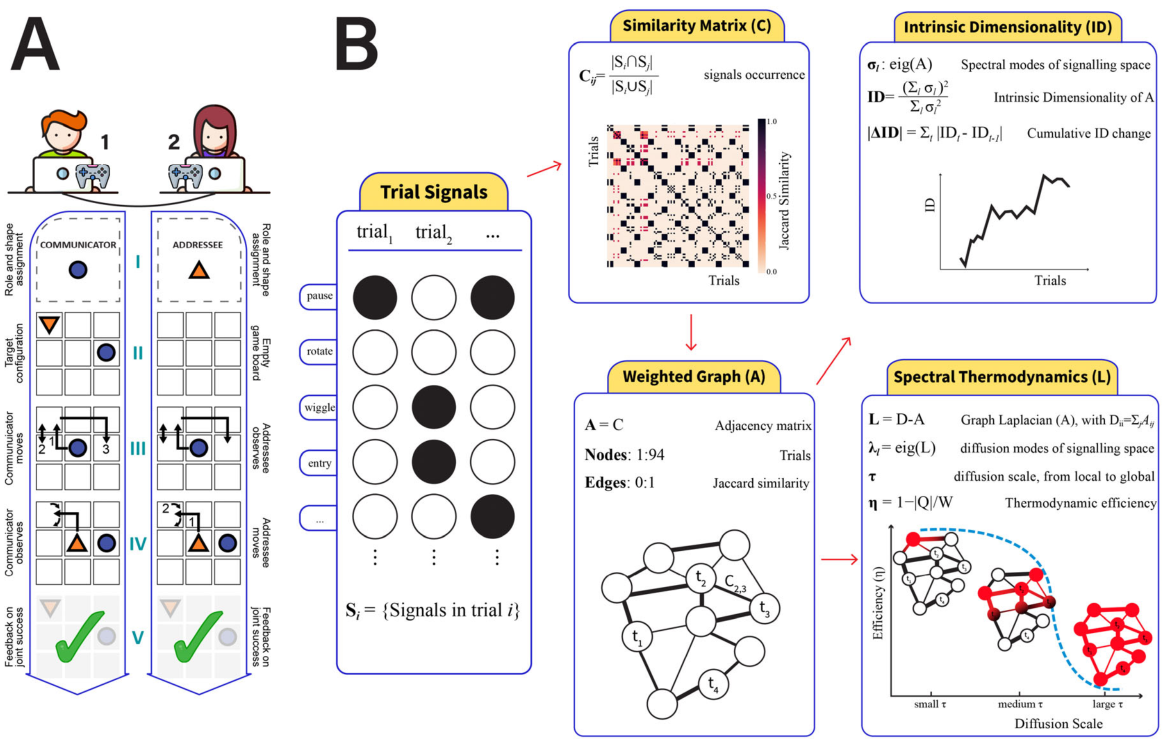

Figure 1: Task and analysis pipeline. **A**) Tacit Communication Game. The Communicator (blue) conveys the Addressee's target position and orientation using only movements of their own token (e.g., a "wiggle" to signal orientation). Because no codebook exists, dyads must invent and stabilize movement-meaning mappings through interaction. **B**) Analysis pipeline. Trial-wise signals are coded (left) and compared to compute a Jaccard similarity matrix C (top), defining a weighted graph A over trials (bottom). Intrinsic Dimensionality (ID), derived from the spectrum of A, quantifies how many independent signaling patterns organize the dyad's signaling space. Spectral thermodynamics, computed from the graph Laplacian of A, characterizes how coordination patterns propagate through this network across diffusion scales τ. In the schematic, red nodes and edges illustrate network regions engaged by diffusion at scales τ, from local to global. Efficiency profile (dashed blue line) indicates the trade-off between entropic cost ($|Q|$) and distribution capacity (W).

threshold and persists only as long as energy continues to flow, exporting entropy to the environment. Order arises precisely because the system is driven away from equilibrium through sustained energy flow (Prigogine & Stengers, 1984).

By way of example, consider two strangers seated together at a dinner party, sharing only tenuous control over a common language. Their initial communicative attempts explore a vast space of signaling options and interpretations. Early exchanges are fragile: successes are accidental, and past behavior exerts little constraint. Over time, however, certain coordination patterns (e.g., ways of moving, timing, attending, or responding) are selectively amplified because they prove locally successful or cognitively economical. At a critical point, diffuse exploration gives way to a coherent pattern, and subsequent behavior is "pulled" into this emerging structure. Maintaining this shared order requires ongoing work: sustaining attention, generating predictions, suppressing alternative interpretations, and repairing breakdowns when they occur (Clark, 1996; Fusaroli & Tylén, 2016; Stolk et al., 2016). In dynamical terms, a shallow, diffuse region of the joint state space is replaced by a deeper basin of attraction. Coordination work is what keeps the coupled trajectories of interlocutors inside that basin: a shared topic, an emerging pact, a mutually recognized frame. This emergent mode functions as an order parameter of the coupled dynamical system formed by the dyad, constraining what can be meant next and reducing the effective dimensionality of the joint system. Crucially, interlocutors create this order parameter, which then comes to enslave their behavior. On this view, meaning-making is an interaction-contingent order parameter that reduces the effective degrees of freedom of a coupled system (Deacon, 2011).

Following this conceptual re-mapping, if meaning-making is order emerging from symmetry-breaking, it should carry thermodynamic signatures. Creating organized structure in hypothesis space from disordered possibilities requires cognitive work, and maintaining that structure against dissolution requires sustained energy flow. Successful meaning-making should therefore be marked by *dimensional compression* (the slaving principle: order parameters reduce degrees of freedom) and *entropic cost* (the thermodynamic price of organization). Furthermore, these two signatures should converge at an intermediate scale: the mesoscale regime where relational structure governs how coordination patterns propagate through the signaling space, rather than at local scales where diffusion probes only immediate neighbors, or global scales where diffusion saturates the network of communicative relations and topological distinctions wash out (Figure 1B, bottom right panel). We test these three predictions using behavioral data from the Tacit Communication Game (TCG), a real-time joint referential task in which dyads invent geometric signals without pre-existing conventions (De Ruiter et al., 2010; Stolk et al., 2013). Each dyad's evolving signal repertoire is modeled as a similarity network and analyzed using spectral graph thermodynamics to track how information diffuses through the network over time (De Domenico & Biamonte, 2016; Ghavasieh & De Domenico, 2024).

Methods

Participants and Task

Sixty-nine dyads (138 participants) completed 94 trials of the TCG, alternating between Communicator and Addressee roles. Communicative problems changed across trials. On each trial, only the Communicator saw the Addressee's target configuration and could convey it solely through movements of their own token—stepwise translations and 90° rotations visible in real time (Figure 1A). To succeed, the Addressee had to interpret part of the Communicator's movement sequence as an ostensive communicative pattern, distinguishing it from instrumental movements used to reach the final configuration, and infer the intended target. Although the referent space was constrained (nine grid positions × token-specific orientations), the signal space was effectively open-ended: different dyads invent different movement-meaning mappings as new communicative challenges arise across trials (Stolk et al., 2014). Success depended on the dyad's ability to stabilize, reuse, and reorganize relations between communicative patterns and referents, on the fly. Accordingly, the task captures communication as a coupled, history-dependent dynamical process rather than a sequence of independent transmissions. Performance was scored as binary accuracy on each trial.

From Signals to Networks

Following established protocols (Blokpoel et al., 2012; Stolk et al., 2014; Wadge et al., 2019), a coder blind to the study's hypotheses classified each trial's communicative signals from offline replays. Signals ranged from brief pauses used to disambiguate locations to rotations or "wiggling" behaviors used to convey orientation (Figure 1A). Multiple signals could occur within a single trial. Because dyad-specific signals are inherently relational rather than lexical, we represented each dyad's signaling history over trials as a 94×94 similarity matrix, defined as the proportion of signals shared between trials *i* and *j* (Jaccard similarity): $C_{ij} = |S_i \cap S_j| / |S_i \cup S_j|$, where S_i denotes the set of signals used on trial *i*. For example, if trial *i* used {pause, wiggle} and trial *j* used {wiggle}, their similarity is 1/2. This matrix captures how similarly a dyad behaved across trials and encodes the relational structure through which their pacts propagate (Figure 1B). We treated it as a weighted adjacency matrix *A*, defining a graph in which nodes correspond to trials and edge weights reflect signal overlap. This representation emphasizes patterns of signals co-occurrence and recurrence, i.e., the level at which signal-referent relations stabilize and symmetry breaking occurs, rather than fine-grained movement kinematics.

Intrinsic Dimensionality. To quantify dimensional compression, we characterized each dyad's similarity network by its Intrinsic Dimensionality (*ID*), computed as the participation ratio of the adjacency spectrum $\boldsymbol{\sigma_l}$ of *A*: $\boldsymbol{ID} = (\sum_l \boldsymbol{\sigma_l})^2 / \sum_l \boldsymbol{\sigma_l^2}$. *ID* quantifies how many independent spectral modes are required to describe the dyad's signaling space. If all trials are equally similar, the spectrum is relatively uniform and *ID* is high. If signaling behavior converges onto a small set of recurring patterns, the spectrum becomes dominated by a few leading eigenvalues and *ID* is low. *ID* thus operationalizes the slaving principle: as coordination stabilizes, emergent order parameters constrain the system's degrees of freedom, reducing effective dimensionality (Haken, 1983). Because stabilization is history-dependent, *ID* was tracked over time using an expanding window. For each trial *t*, *ID(t)* was computed on the subnetwork comprising trials 1 through *t*. We also computed $|\boldsymbol{\Delta ID}| = \sum_{t=2}^{T} |\boldsymbol{ID_t} - \boldsymbol{ID_{t-1}}|$, the sum of absolute changes in *ID* across trials, to quantify cumulative dimensional volatility. High $|\Delta ID|$ indicates greater overall restructuring of the signaling space, whereas low values indicate early stabilization into a basin of attraction.

Spectral Thermodynamics. Following Ghavasieh & De Domenico (2024), we analyzed diffusion dynamics on each dyad's similarity network to probe how coordination patterns propagate across timescales. Starting from the adjacency matrix *A* and corresponding weighted degree matrix *D*, the graph Laplacian is $L = D - A$. We then computed the density matrix $\rho(\tau) = exp(-\tau L)/Z(\tau)$, where $Z(\tau)$ is the partition function and τ is the diffusion timescale parameter that acts as a lens for probing network organization at different resolutions. At small τ, diffusion explores only immediate neighbors, i.e., local signal co-occurrence. At large τ (τ_{late}), diffusion saturates the network and topological distinctions are washed out. The mesoscale regime lies between these extremes, where relational constraints govern how signaling patterns propagate through the signaling space. We characterized this regime using three timescales: τ_{peak} (where efficiency reaches its maximum within the spectral window bounded by the largest Laplacian eigenvalue), τ_{window} (the geometric center of the mesoscale range), and τ_{knee} (the inflection point where efficiency begins its steepest decline toward saturation). At each scale τ, pathway diversity, i.e., how many distinct routes coordination patterns can take through the signaling space, is quantified by the von Neumann entropy $S(\rho) = -Tr(\rho \log \rho)$. $Z(\tau)$ and $S(\rho)$ define the transport capacity $W(\tau) = -(1/\tau)log(Z(\tau)/N)$ and the entropic cost $|Q(\tau)| = (S(\tau) - log N)/\tau$. In this thermodynamic mapping, *W* represents the network's capacity to distribute information—the "work" done by its relational structure—while $|Q|$ represents the "cost" in terms of lost response diversity—the entropic price paid by the dyad to prune the signaling space into a shared, stable pact. Thermodynamic efficiency $\eta(\tau) = 1 - |Q(\tau)|/W(\tau)$ captures the trade-off between these quantities: high efficiency indicates effective transport without sacrificing diversity; low efficiency indicates substantial entropic cost to maintain organized structure. Efficiency was computed across each dyad's spectral range and summarized using area under the curve (AUC_η). To interpret these signatures, we compared real networks against two null models (50 realizations per dyad). Erdős-Rényi (ER) nulls randomize connectivity while preserving weight distributions. Configuration Model (CM) nulls preserve the empirical degree sequence, which signals were used and how often, while randomizing how signals connect to each other. Comparisons with CM nulls thus isolate effects of topological organization beyond signal frequency alone. The efficiency deficit ($\Delta AUC = Real - CM$) tests whether the observed relational structure carries entropic costs beyond those expected from signal usage statistics.

Results

Dimensional Compression Predicts Success

Communicative success was systematically associated with reduced dimensionality of the signaling space. Full-network dimensionality (ID_{final}) correlated negatively with accuracy ($r = -.26$, $p = .033$; Figure 2A): dyads achieving higher accuracy did not maximize signaling variety but instead converged on a more constrained repertoire of coordinative modes, or shared ways of signaling. Structural volatility showed a similar pattern. $|\Delta ID|$, the total amount of dimensional restructuring over the interaction, also predicted failure ($r = -.30$, $p = .013$; Figure 2B): unsuccessful dyads exhibited greater cumulative restructuring of their signaling space, whereas successful dyads were characterized by greater overall stability, consistent with convergence into a stable basin of attraction. Trajectory analyses revealed the dynamics underlying these endpoint effects. Both high- and low-success dyads expanded their signaling spaces during early trials, reflecting exploratory search as well as the increase in ID induced by accumulating observations (Figure 2C). As interaction progressed, however, successful dyads slowed this expansion, while unsuccessful dyads continued to accumulate representational complexity across trials. This divergence reflects the predicted symmetry-breaking dynamics: both groups begin with diffuse, exploratory signaling, but only successful dyads transition towards a lower-dimensional signaling manifold (Figure 2D). The magnitude of dimensional compression achieved by communicators was dramatic relative to the growing space of possibilities (Figure 2E, F). By the final trial, real dyads exhibited a mean ID of 4, compared to 31 and 27 for ER and CM nulls, a sixfold reduction. Trial-to-trial ID volatility showed an even larger eightfold difference, with $|\Delta ID| \approx 0.03$ for real dyads versus ≈ 0.26 for null networks. Human signaling networks are not merely constrained; they actively compress the joint state space that random growth would otherwise produce. This divergence indicates that signaling pacts are actively sculpted relational structures, rather than samples drawn from a pre-existing distribution. This is not merely a reduction in behavioral variety, but the construction of a shared state space in which certain trajectories become attractors while others recede into the background—the spectral signature of emergent order parameters.

Success Carries an Entropic Cost

If dimensional compression reflected mere signal simplification, successful dyads should show higher thermodynamic efficiency—streamlined networks with direct pathways. We observed the opposite. Integrated thermodynamic efficiency (AUC_η) correlated negatively with communicative success ($r = -.39$, $p = .001$; Figure 3A): dyads achieving higher accuracy exhibited lower efficiency, paying a greater entropic cost per unit of information transport. This pattern is paradoxical under transmission-optimization accounts but expected if communication actively constructs structure from disordered possibilities. Critically, this efficiency deficit was not driven by signal frequency. When each dyad was compared to its degree-matched CM baseline (preserving how often signals were used while randomizing their relational organization), the efficiency deficit (ΔAUC) remained predictive of success ($r = -.37$, $p = .002$; Figure 3B). What mattered was not which signals were deployed, but how

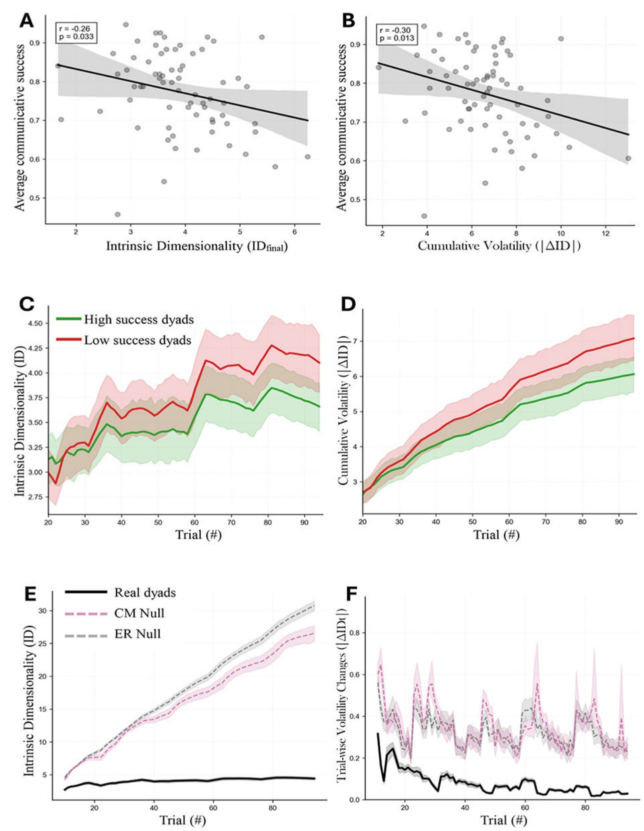

Figure 2. Dimensional compression predicts communicative success. **A,B)** Greater signaling-space complexity (ID_{final}) and cumulative volatility ($|\Delta ID|$) are associated with lower success (69 dyads). **C,D)** Trajectories of expanding-window ID and $|\Delta ID|$ for high- and low-success dyads (median split). Both groups increase in dimensionality, but successful dyads constrain this expansion. **E)** $ID(t)$ trajectories for real dyads versus ER and CM nulls. **F)** Trial-wise signaling volatility changes ($|\Delta ID_t|$) converges for real dyads, while it remains high for ER and CM nulls. Shading: 95% CI across real dyads or null networks (200 per dyad).

they were relationally organized: how signal-referent pathways were topologically structured to differentiate meanings while maintaining robustness within meaning categories. The relational architecture imposed by human dyads thus carries an entropic cost beyond what would be expected from signal usage alone. Notably, this cost was most pronounced at intermediate diffusion scales (Figure 3C), precisely where mesoscale relational structure governs coordination dynamics.

Scale Convergence Validates the Framework

If spectral thermodynamics captures organizational structure relevant to meaning-making, its signatures should converge with geometric measures at the mesoscale, where signaling pacts constrain coordination, and decouple once diffusion saturates the network. This is what we observed. At intermediate diffusion timescales (τ_{peak}, τ_{window}, τ_{knee}), transport gain *W* correlated strongly with *ID* ($r_s = -.84$ to $-.89$, all $p < .001$) and with $|\Delta ID|$ ($r_s = -.68$ to $-.74$). Entropic cost $|Q|$ showed its strongest coupling at τ_{knee}, the inflection point where efficiency trade-offs are sharpest ($r = -.91$; Figure 3D). This pattern identifies τ_{knee} as a critical regime in which organizational constraints exert maximal influence over the thermodynamic budget of communication. These correlations indicate that thermodynamic capacity for information transport and geometric constraint on signaling dimensionality reflect two facets of the same underlying organization. By contrast, at later diffusion timescales (τ_{late}), all correlations became non-significant (rs $= -.15$ to $-.21$, ps $> .09$; Figure 3E). Once diffusion has traversed the full network, organizational structure is no longer resolvable, and the convergence between geometric and thermodynamic measures disappears. Taken together, this scale-dependent convergence demonstrates that both manifold geometry and spectral thermodynamics index the same mesoscale structure that supports successful coordination, consistent with prior evidence that meaningful network organization operates at intermediate diffusion scales (Ghavasieh & De Domenico, 2024).

Discussion

This contribution explores a central problem in human communication: how interlocutors construct a shared signal-referent space when no such space is given in advance. Using principles of complex dynamical systems, we have argued that building this shared space should exhibit two defining signatures, dimensional compression and entropic cost. We provide empirical evidence for both. Communicatively successful dyads formed signaling manifolds that were simultaneously low-dimensional, reflecting the emergence of order parameters enslaving behavior, and topologically differentiated, supporting distinct pathways to distinct referents. Achieving this organized relational structure came with an entropic cost: successful dyads showed reduced thermodynamic efficiency relative to control graphs matched for signal frequency, indicating that communicative success depends on the cognitive work of constructing shared structure rather than selecting within a pre-specified space.

The efficiency deficit observed in communicating dyads appears paradoxical if one follows the intuition that communicative coordination leads to more efficient use of cognitive resources (Fedorenko et al., 2024). The paradox

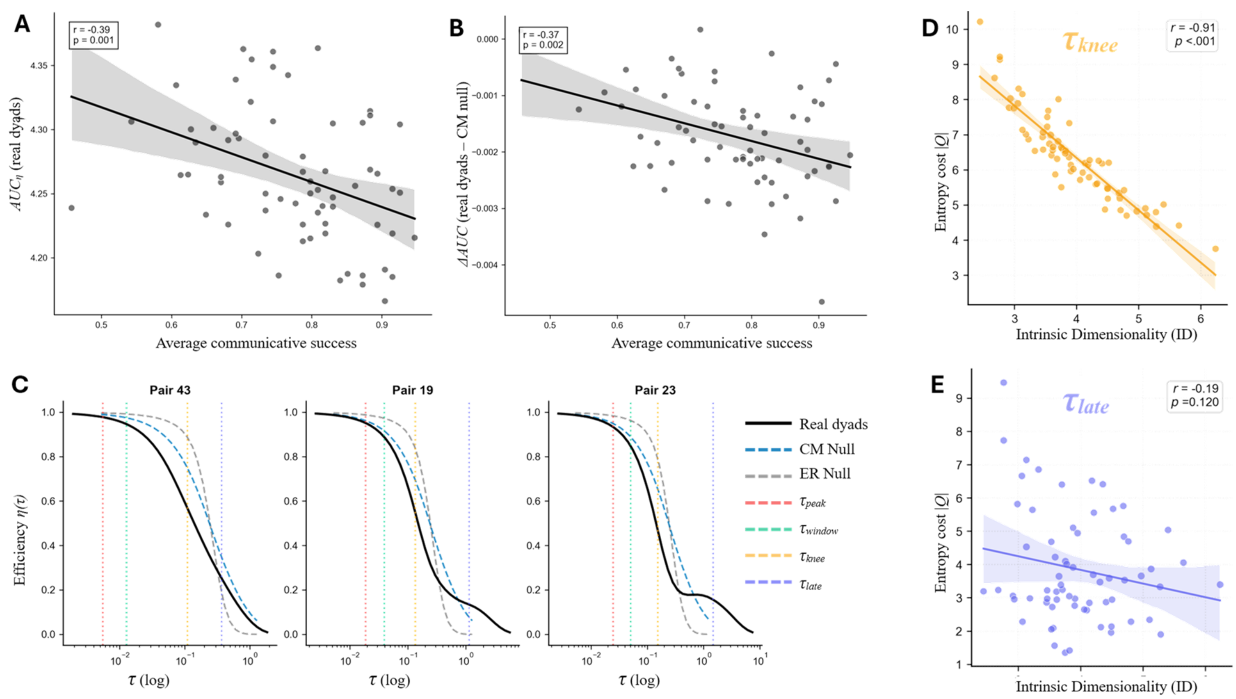

Figure 3. Successful meaning-making carries an entropic cost. **A)** Integrated thermodynamic efficiency AUC_η as a function of communicative success (69 dyads). **B)** Efficiency deficit ΔAUC relative to degree-matched null networks, as a function of communicative success. **C)** Thermodynamic efficiency profiles $\eta(\tau)$ for three representative dyads, showing that real dyads networks exhibit lower efficiency than ER and CM nulls at mesoscale diffusion timescales (τ_{knee}). **D, E)** Entropic cost $|Q|$ is strongly correlated with *ID* at τ_{knee}, but not at τ_{late}.

dissolves once we consider where optimization happens. In experimental worlds where communicators select from a small, transparent set of alternatives, the hypothesis space has already been optimized, by the experimenter. Under such conditions, high thermodynamic efficiency is expected. In contrast, semiotically open contexts, e.g., everyday communication or TCG-like challenges, require interlocutors to construct and stabilize new signal-referent relations from a large space of possibilities. The greater entropy expenditure observed in successful dyads is therefore not a failure of optimization, but the computational signature of actively sculpting a shared referential structure.

What does this entropic cost buy? The conjunction of dimensional compression (low *ID*) with pathway diversity (high $|Q|/W$ ratio) suggests that successful dyads construct signaling manifolds that are simultaneously constrained and redundant. To ensure that a particular signal—say, a "wiggle" indicating orientation, or an emphatic pause marking target location—reliably refers to one referent rather than another, dyads must build relational structures that preserve multiple routes to the same meaning while suppressing crosstalk between distinct referential domains. Entropic cost reflects the maintenance of these differentiated pathways, while dimensionality compression reflects the confinement of behavioral trajectories within the resulting basins of attraction. What appears inefficient from a standard optimization perspective is adaptive from a communicative perspective: the efficiency deficit is the price of referential clarity under conditions of nascent semiotic organization.

Three theoretical implications follow. First, the dramatic separation between real dyads and null models ($ID \approx 4$ versus 27–31) demonstrates that signaling pacts are actively sculpted relational structures rather than samples selected from a pre-existing distribution. This challenges transparency assumptions that underwrite Bayesian and active inference accounts of communication (Friston & Frith, 2015; Goodman & Frank, 2016), which presuppose a mutually known hypothesis space. The observed effects cannot be explained by selection within such a space; they require construction of the space itself. *Second*, the divergence of interaction trajectories (Figure 2C, D) shows that communicative coordination is fundamentally path dependent. Interaction history is not noise to be averaged away, but a constitutive ingredient of meaning-making, challenging stationarity assumptions common in pragmatic modeling. Although both high- and low-success dyads initially expand their signaling spaces, only successful dyads constrain this expansion and maintain lower dimensionality over the remainder of the interaction. This temporal signature—early exploration followed by gradual stabilization—cannot be captured by approaches that aggregate across trials or assume stationary dynamics. *Third*, the predictive power of relational organization beyond signal frequency challenges surface-alignment accounts of communication (Pickering & Garrod, 2004). The finding that efficiency deficits relative to degree-matched baselines predict success shows that communicative outcomes depend not on which signals are used, but *how* those signals connect. This distinction is invisible to approaches that focus on signal frequency or surface alignment. What supports communication is the low-dimensional organization of the dyad's joint state space, not the surface forms each partner uses to move through it (Hallajian et al., 2025; Poncelet-Romaneli et al., 2025).

This framework reconceptualizes the nature of communicative work. In Shannon's framework, information is uncertainty reduction over fixed alternatives; in active inference, agents minimize prediction error within generative models presupposing hypothesis-space structure. Both assume that communication unfolds against a pre-existing backdrop of shared possibilities. Our results instead suggest that the primary computational challenge lies in constructing and maintaining that backdrop itself (Clark, 1996; Stolk et al., 2020): establishing what counts as a referent, which distinctions matter, and how signals relate to those distinctions. This is *coordination work*: the sustained investment of attention, prediction, and repair required to build the shared frame that makes meaning possible. Spectral thermodynamics provides formal tools for quantifying this work, revealing that successful coordination is marked not by effort minimization but by strategic entropy expenditure for relational organization.

Further empirical tests can evaluate the generalizability of this framework. First, the findings need confirmation using natural dialogue. Embeddings from large language models provide continuous semantic spaces from which similarity networks can be constructed without categorical annotation, enabling application of this approach to naturalistic conversational data. Second, the framework generates predictions for neural implementation. Prior work has identified the right posterior superior temporal sulcus and anterior temporal regions as critical for communicative coordination (Redcay et al., 2016; Stolk et al., 2013). The present framework predicts that entropy production and efficiency deficits will covary with activity in these regions during successful meaning-making. Third, the approach extends naturally to multi-party interaction and transmission chains, where a central question is whether efficiency inversion scales with group size or whether population-level dynamics dilute the costly relational structure observed in dyads.

In summary, by treating human communication as a far-from-equilibrium process unfolding in a state space of latent hypotheses, this work suggests a computational-level mechanism through which interlocutors come to understand one another: the construction of a shared manifold of possible meanings. We have shown that meaning-making consumes entropy to reduce dimensionality in a dyad’s network of signal-referent relations. Entropic cost reflects the construction of redundant, differentiated pathways through which signals reliably reach referents. Low dimensionality reflects the confinement of behavior to those pathways once they stabilize. Together, these dynamics instantiate a symmetry-breaking phase transition through which a high-dimensional hypothesis-space of possibilities becomes compressed into a shared, low-dimensional referential structure that makes communication possible.

References

Binmore, K. (2009). *Rational Decisions*. Princeton University Press. https://doi.org/10.1515/9781400833092

Blokpoel, M., van Kesteren, M., Stolk, A., Haselager, P., Toni, I., & Van Rooij, I. (2012). Recipient design in human communication: Simple heuristics or perspective taking? *Frontiers in Human Neuroscience*, *6*. https://doi.org/10.3389/fnhum.2012.00253

Brennan, S. E., & Clark, H. H. (1996). Conceptual pacts and lexical choice in conversation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*(6), 1482.

Clark, H. H. (1996). *Using language*. Cambridge University Press.

De Domenico, M., & Biamonte, J. (2016). Spectral Entropies as Information-Theoretic Tools for Complex Network Comparison. *Physical Review X*, *6*(4), 041062. https://doi.org/10.1103/PhysRevX.6.041062

De Ruiter, J. P., Noordzij, M. L., Newman-Norlund, S., Newman-Norlund, R. D., Hagoort, P., Levinson, S. C., & Toni, I. (2010). Exploring the cognitive infrastructure of communication. *Interaction Studies*, *11*(1), 51–77. https://doi.org/10.1075/is.11.1.05rui

Deacon, T. W. (2011). *Incomplete nature: How mind emerged from matter*. WW Norton & Company.

Friston, K. J., & Frith, C. D. (2015). Active inference, communication and hermeneutics. *Cortex*, *68*, 129–143. https://doi.org/10.1016/j.cortex.2015.03.025

Fedorenko, E., Ivanova, A. A., & Regev, T. I. (2024). The language network as a natural kind within the broader landscape of the human brain. Nature Reviews Neuroscience, 25(5), 289–312. https://doi.org/10.1038/s41583-024-00802-4

Fusaroli, R., & Tylén, K. (2016). Investigating Conversational Dynamics: Interactive Alignment, Interpersonal Synergy, and Collective Task Performance. *Cognitive Science*, *40*(1), 145–171. https://doi.org/10.1111/cogs.12251

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

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

Ghavasieh, A., & De Domenico, M. (2024). Diversity of information pathways drives sparsity in real-world networks. *Nature Physics*, *20*(3), 512–519. https://doi.org/10.1038/s41567-023-02330-x

Goodman, N. D., & Frank, M. C. (2016). Pragmatic Language Interpretation as Probabilistic Inference. *Trends in Cognitive Sciences*, *20*(11), 818–829. https://doi.org/10.1016/j.tics.2016.08.005

Haken, H. (1983). Synergetics. An introduction. *Springer Series in Synergetics*.

Hallajian, A.-H., Koch, S. B. J., Bašnáková, J., Toni, I., & Stolk, A. (2025). Alignment of Representational Complexity as a Latent Control Parameter in Referential Communication. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *47*. https://escholarship.org/uc/item/67c9j72j

Helbing, D., Keltsch, J., & Molnár, P. (1997). Modelling the evolution of human trail systems. *Nature*, *388*(6637), 47–50. https://doi.org/10.1038/40353

Pickering, M. J., & Garrod, S. (2004). Toward a mechanistic psychology of dialogue. *Behav Brain Sci*, *27*, 169–190.

Poncelet-Romaneli, M., Glasman, T., Hallajian, A. H., Bašnáková, J., Galantucci, B., & Toni, I. (2025). Fine-tuning conceptual structure of referents through coordinated interaction. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *47*. https://escholarship.org/uc/item/67c9j72j

Prigogine, I., & Stengers, I. (1984). *Order Out of Chaos: Man's New Dialogue with Nature*. Bantam Books.

Redcay, E., Velnoskey, K. R., & Rowe, M. L. (2016). Perceived communicative intent in gesture and language modulates the superior temporal sulcus. *Human Brain Mapping*, *37*(10), 3444–3461. https://doi.org/10.1002/hbm.23251

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*, 379–423.

Stolk, A., Bašnáková, J., & Toni, I. (2020). Joint epistemic engineering: The neglected process of context construction in human communication. In *Routledge Handbook of Neurosemiotics* (pp. 259–278). Routledge. https://repository.ubn.ru.nl/bitstream/handle/2066/285146/285146.pdf?sequence=1

Stolk, A., Noordzij, M. L., Verhagen, L., Volman, I., Schoffelen, J.-M., Oostenveld, R., Hagoort, P., & Toni, I. (2014). Cerebral coherence between communicators marks the emergence of meaning. *Proceedings of the National Academy of Sciences*, *111*(51), 18183–18188. https://doi.org/10.1073/pnas.1414886111

Stolk, A., Verhagen, L., Schoffelen, J.-M., Oostenveld, R., Blokpoel, M., Hagoort, P., van Rooij, I., & Toni, I. (2013). Neural mechanisms of communicative innovation. *Proceedings of the National Academy of Sciences*, *110*(36), 14574–14579.

Stolk, A., Verhagen, L., & Toni, I. (2016). Conceptual Alignment: How Brains Achieve Mutual Understanding. *Trends in Cognitive Sciences*, *20*(3), 180–191. https://doi.org/10.1016/j.tics.2015.11.007

Wadge, H., Brewer, R., Bird, G., Toni, I., & Stolk, A. (2019). Communicative misalignment in Autism Spectrum Disorder. *Cortex*, *115*, 15–26. https://doi.org/10.1016/j.cortex.2019.01.003