Pink noise in speakers' semantic synchrony dynamics predicts conversation quality

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Abstract

Dyadic social interaction is a complex coordination task involving many interconnected variables. Previous research has shown that metastability – persistence for an extended, but impermanent, period of time in a non-stable state of a system – can be a useful lens for understanding what makes an interaction successful. Metastability occurs at certain noise signatures; namely, pink noise, in which the power of a signal is inverse to its frequency. However, this framework has thus far only been applied to para-conversational signals like heart rate and prosody – not to the semantic content of a conversation. Here, we present pink noise analysis of semantic trajectories as a metric for conversational success and apply this technique to a large open conversation dataset. Our results demonstrate that adaptive movement in and out of semantic synchrony in a conversation predicts a host of variables representing conversation quality.

Keywords: Dynamical systems; Social cognition; Conversation

Introduction

When we enter into a conversation, we're faced with a complex coordination task. We must make inferences about our interlocutor's beliefs, intuit when to start talking, and manage countless other negotiations in real time. With so many interacting features at play, modeling dyadic conversation can become intractable. Studying dyadic interaction in terms of interpersonal synchrony can be a helpful way to manage that complexity.

Much of the interpersonal synchrony literature focuses on synchrony as a predictor of success in social interaction (see Mogan et al. (2017) for a review). However, some recent work has suggested that synchronizing with an interactive partner can also be maladaptive (Abney et al., 2015; Timmons et al., 2015; Feniger-Schaal et al., 2018; Pérez et al., 2016; Galbusera et al., 2019). In response to these seemingly contradictory findings, a subliterature has emerged that highlights the importance not of (a)synchrony itself, but of social partners' ability to adaptively move in and out of synchrony (Mayo & Gordon, 2020; Wallot et al., 2016; Dahan et al., 2016; Hale et al., 2020; Wohltjen & Wheatley, 2021; Ravreby et al., 2022). Borrowing from complex dynamical systems (see Kelso (2021)), this idea of adaptive movement in and out of synchrony with a social partner can be operationalized as pink noise, or $\frac{1}{f}$ noise scaling. Thus far, pink noise in dyadic interaction has only been studied in para-conversational signals like heart rate. Here, we demonstrate that this approach can be extended to the actual semantic content of a conversation.

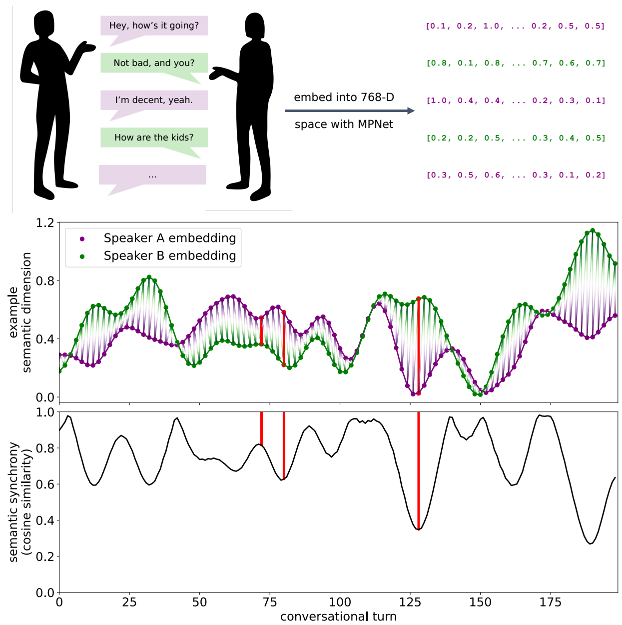

Figure 1: Calculating semantic synchrony timecourse for an example conversation. Each turn is embedded into high-dimensional encoding space with a transformer. Then, the cosine similarity between pairs of adjacent turns forms a continuous measure of semantic synchrony.

Methods

Dataset

We used an open dataset, CANDOR (Reece et al., 2023), which consists of 1,656 conversations between strangers (mean: 31 minutes; SD: 7.96 minutes). After each conversation, participants took extensive surveys about their personalities and experiences. We separated the 205 numeric survey questions into 6 categories: those relating to (1) conversation enjoyment, (2) sense of connection, (3) engagement and memory, (4) low-level conversation statistics, (5) perception of partner's traits, and (6) one's own traits.

Pink noise analysis

First, we segmented each conversation transcript into turns, splitting the text each time a new speaker began an utterance (Figure 1, top left). Then we embedded each turn into high-D semantic space (Figure 1, top right) (Reimers & Gurevych, 2019). The results in this paper were generated using *all-mpnet-base-v2* and its 768-dimensional space, but we also calculated scaling coefficients with roBERTa, sBERT, and LaBSE to ensure that this method is robust to different embedding regimes (Liu et al., 2019; Reimers & Gurevych, 2019; Feng et al., 2022).

To calculate the semantic synchrony signal, we took the cosine similarity of the embeddings of each pair of adjacent turns (Figure 1, middle and bottom). For a conversation consisting of N turns, this gave us a length $N-1$ measure of how closely aligned partners were in their semantic content at each timepoint.

To assess the color of noise present in each conversation's semantic synchrony signal, we calculated a scaling coefficient with detrended fluctuation analysis (Rydin Gorjão et al., 2022). A scaling coefficient of 1 indicates pink noise, while 0 indicates white noise and 2 indicates red noise.

To test the degree to which pink noise signatures were actually due to moment-to-moment mutual adaptation, for each conversation, we compared the semantic-synchrony signal's scaling coefficient to a distribution of null coefficients generated by scrambling timepoint labels of the semantic-synchrony signal 1,000 times. This gave us a Pink Noise Robustness (PNR) value: the proportion of scaling coefficients from the scrambled distribution that were lower (i.e., whiter noise) than that of the original signal.

Additionally, we wanted to test whether the dyad – rather than each speaker – was the fundamental unit of this adaptive synchrony signal. To do this, we generated a PNR score for each individual's half of a conversation. We also wanted to test against the simpler hypothesis that synchrony itself (not adaptive synchrony) makes for good (or bad) conversation, so we generated an average synchrony score for each conversation.

Predicting conversation variables

We took two approaches to testing whether pink-noise signatures predicted conversation outcomes. First, we correlated PNR scores with participants' responses for each of the 205 post-conversation survey variables across conversations (Pearson for continuous variables, Spearman for discrete). We used two forms of multiple hypothesis correction: Bonferonni correction for a stringent cutoff, and Benjamini/Hochberg False Discovery Rate (FDR) correction for a more lenient cutoff. We then tested whether survey questions about conversation enjoyment were over-represented in the subset of variables correlated with PNR. Second, we performed principal component analyses within each question category, and predicted the score on the first principal component for each conversation with a linear model of the form $category\_composite \sim conversation\_PNR + speaker\_PNR + mean\_synchrony$.

Results

Semantic synchrony trajectories in dyadic conversations exhibit pink noise signatures

The CANDOR conversations yielded a distribution of scaling coefficients ranging between white and pink noise, with a shift towards pinker noise (mean = 0.62, SD = 0.08) and a left-tailed distribution of PNR values (mean = 0.82, SD = 0.22). This indicates that a grand majority of conversations in the CANDOR corpus contained pink noise signatures largely attributable to participants' turn-by-turn navigation in and out of semantic synchrony.

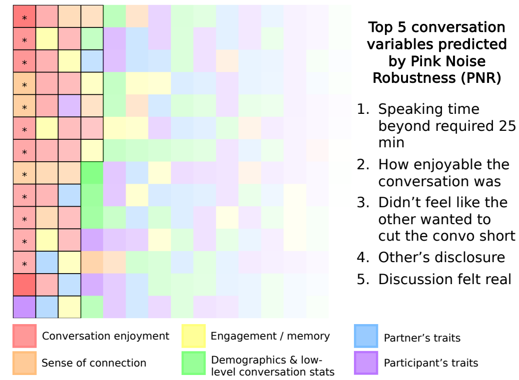

Figure 2: Correlations of pink noise signatures with 205 variables in CANDOR conversations. Color: category; transparency: strength of correlation w/ PNR. Boxes outlined in black: significantly correlated w/ PNR after FDR correction. Asterisks: significantly correlated w/ PNR after Bonferonni correction. Conversation enjoyment and sense of connection variables are significantly overrepresented.

Pink noise robustness selectively predicts post-conversation evaluations of enjoyment and connection

In the set of post-conversation survey variables predicted by PNR scores (49 under FDR correction and 12 under Bonferroni correction), the enjoyment and connection categories were significantly overrepresented ($X^2 = 42$, $p < 0.001$ and $X^2 = 54$, $p < 0.001$ for each correction method respectively; Fig. 2).

For the linear models of form $category\_composite \sim conversation\_PNR + speaker\_PNR + mean\_synchrony$, conversation PNRs were significantly predictive of conversation enjoyment and connection ($p < 0.003$ and $p < 0.03$ respectively), while individual speakers' PNRs did not significantly predict any of the category composites. Average conversational synchrony, on the other hand, was a significant *negative* predictor of all six category composites. This indicates that overall synchrony was not conducive to enjoyment and connection in this dataset, did not operate specifically on enjoyment, and could not explain all variance accounted for by PNR.

Conclusions

Here, we demonstrate that (a) pink noise signatures exist in semantic synchrony during dyadic conversation, (b) these signatures are driven by dynamic adaptation, and (c) these signatures predict speakers' enjoyment of the conversation. Using just the transcript of a conversation, we can measure how effectively two people navigate the complex dynamics of moving in and out of semantic synchrony with each other. By using mathematical tools that were built for understanding systems as a whole – rather than focusing on individual pieces – we can better understand conversation as a complex and dynamic cognitive process.

Acknowledgments

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