Modeling the emergence of cognitive structures for the acquisition of vowel dynamics during early infancy using manifold alignment

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Introduction

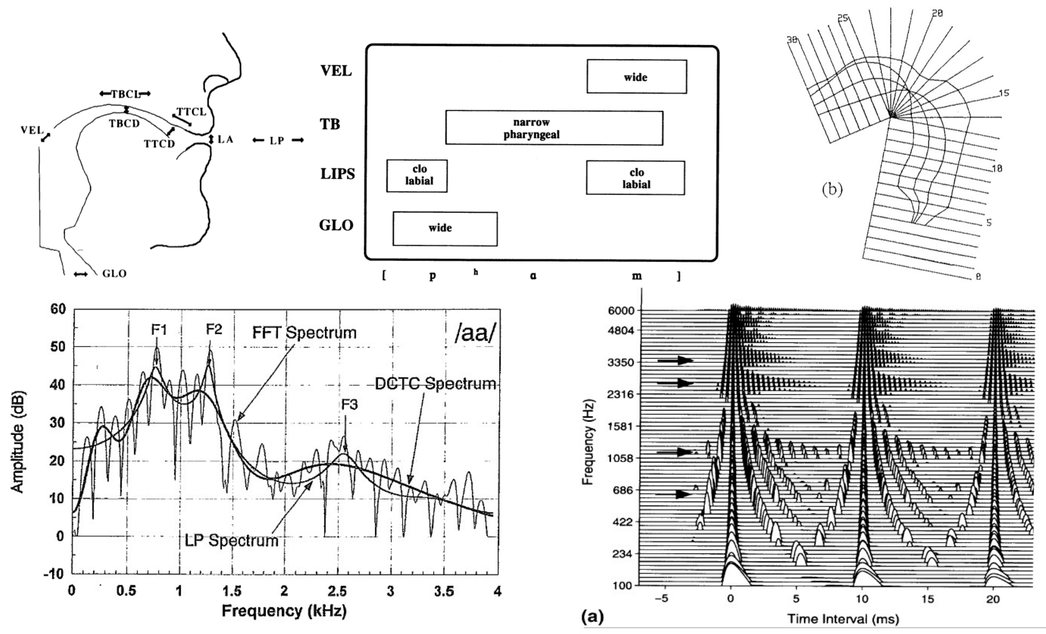


Figure: (top) Figures 1 (left) and 3 (center) from Browman and Goldstein (1989), and Figure 3 from Maeda (1990). (bottom) Figure 2 from Zahorian and Jagharghi (1993) (left) and Figure 3 (right) from Irino and Patterson (2002).

- Vowel dynamics is a complex concept that branches across three broad areas of speech and language research:

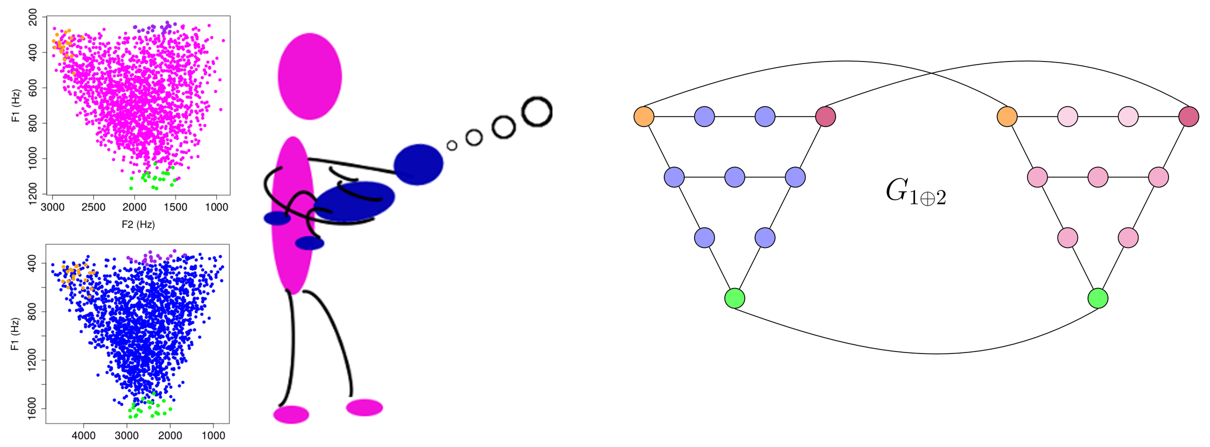
  Articulatory Dynamics : the specification of the motion of articulators during the production of vowels, typically described at several levels of motor control,

  Acoustical Dynamics : the formulation of acoustic measures that are meant to encode the transitional aspects of familiar “static” acoustic properties,

  Auditory Dynamics : the modeling of the perceptual capacities of the auditory system, which capture its sensitivity to a number of temporal aspects of sound internalization.

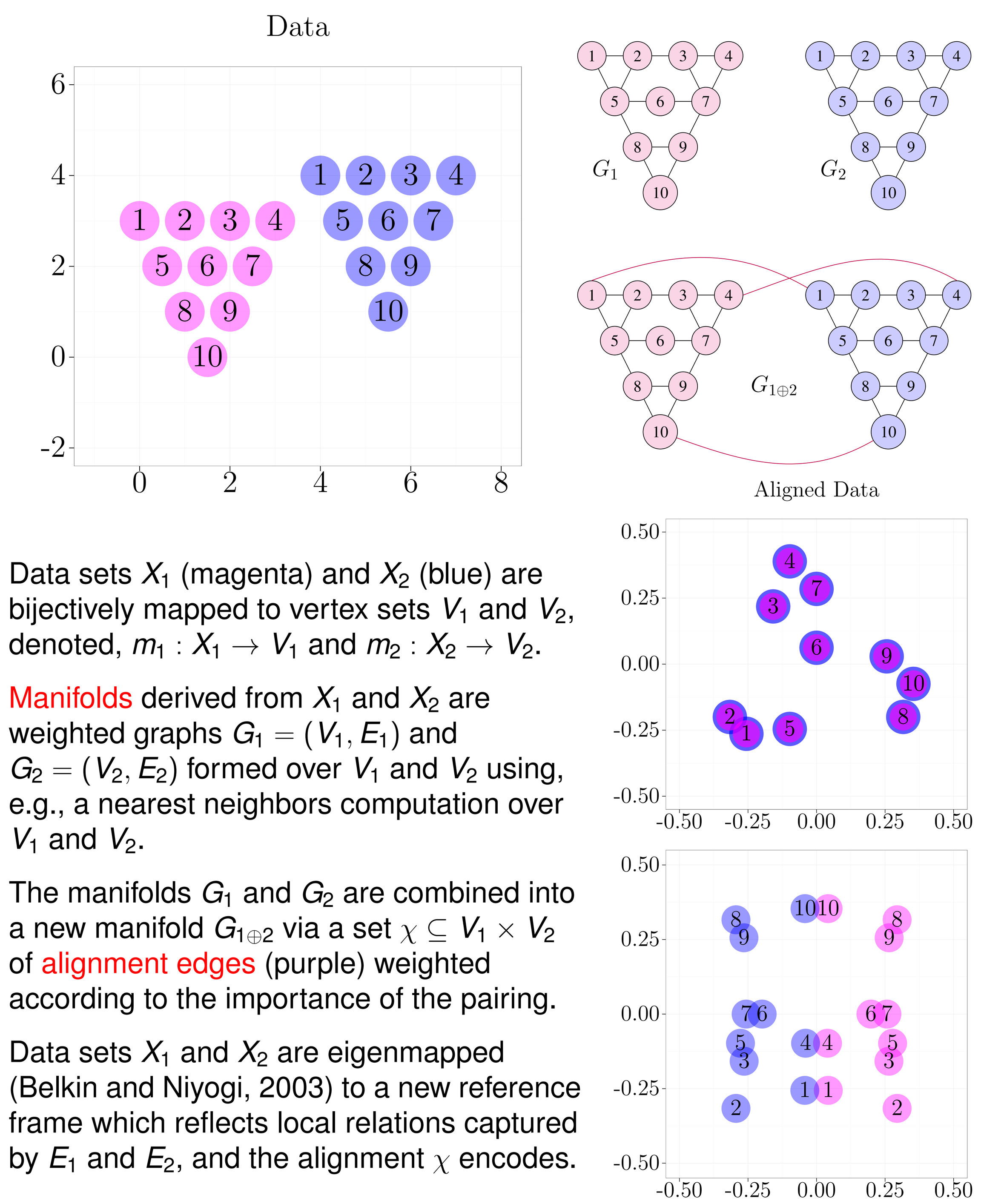
- While much insight has been achieved, very little is known about how infants acquire cognitive structures that undergird the cognitive representation of vowel dynamics.

Cognitive Manifolds and Graph Methods



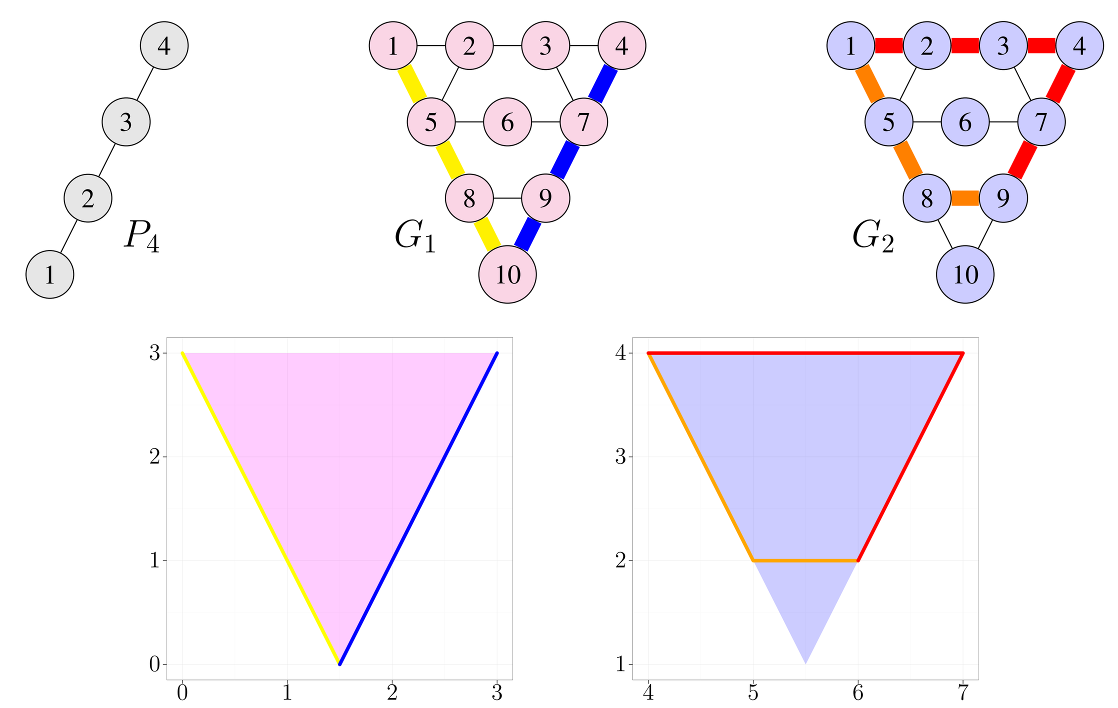
- We put forward a computational model of the emergence of cognitive structures, called cognitive manifolds, that facilitate the acquisition of vowel dynamics during early infancy and are derived from an infant’s vocal interaction with caregivers.
- The principle computation within the framework, called manifold alignment (Lee et al. 2005, Wang, 2010), generates new manifolds that yield mappings of vowel production representations onto structures that facilitate, inter alia:
  - an infant’s representation of vowel-vowel segmental combinations, and
  - an infant’s formation of preliminary relations between their own vowel-vowel sequences and those of their caregivers.
- Moreover, the structural operations provided by the formation of aligned manifolds based on vowel production representations derived from infants and their caregivers serve as a basis for the creation of units that may enter into paradigmatic structures.

Manifold Formation and Laplacian Eigenmapping



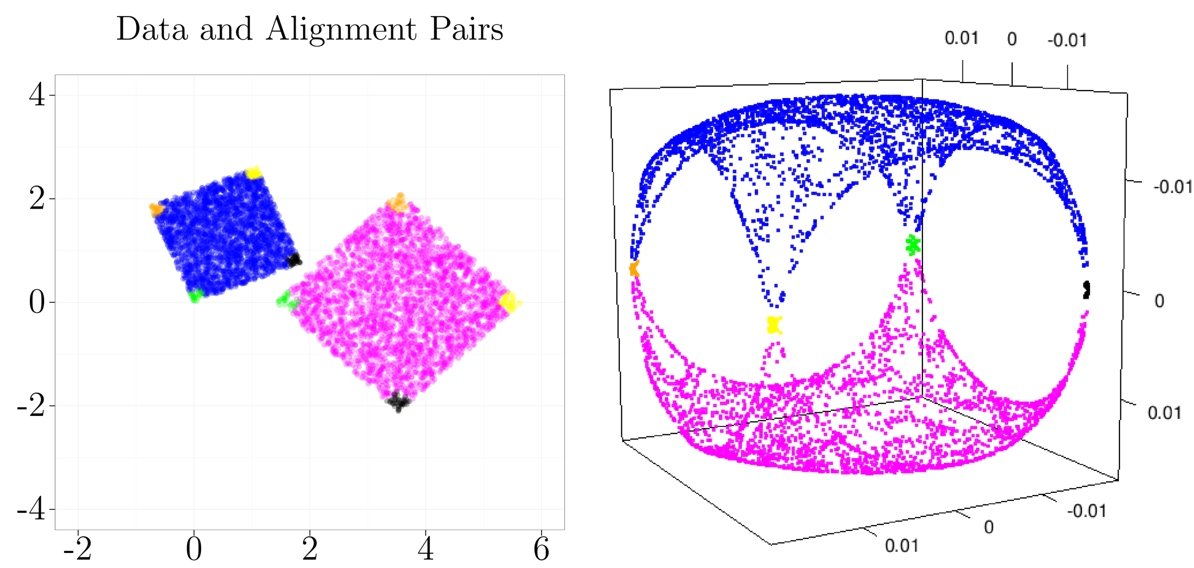
1. Data sets X_1 (magenta) and X_2 (blue) are bijectively mapped to vertex sets V_1 and V_2, denoted, $m_1 : X_1 \rightarrow V_1$ and $m_2 : X_2 \rightarrow V_2$.
2. Manifolds derived from X_1 and X_2 are weighted graphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ formed over V_1 and V_2 using, e.g., a nearest neighbors computation over V_1 and V_2.
3. The manifolds G_1 and G_2 are combined into a new manifold $G_{1\oplus2}$ via a set $\chi \subseteq V_1 \times V_2$ of alignment edges (purple) weighted according to the importance of the pairing.
4. Data sets X_1 and X_2 are eigenmapped (Belkin and Niyogi, 2003) to a new reference frame which reflects local relations captured by E_1 and E_2, and the alignment χ encodes.

Paths and Trajectories

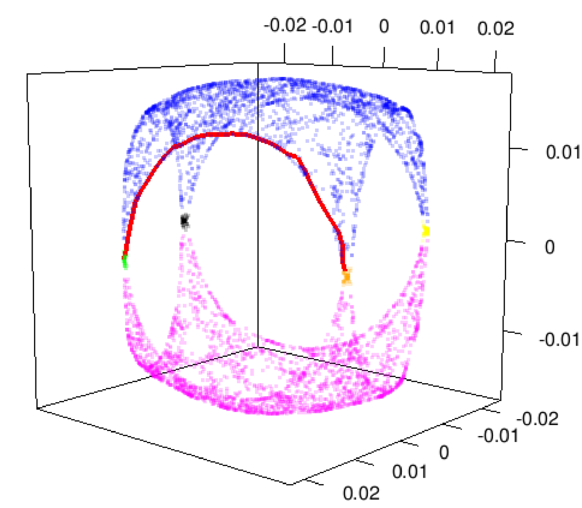


- A path graph of order n, denoted P_n, is a graph with n vertices, exactly two of which have degree 1, while all others have degree 2. A path of order n in a graph $G = (V, E)$ is a subgraph of G that is graph isomorphic to P_n.
- While paths are not inherently directional, directionality can be attributed to a path p by treating it as a sequence $v_1v_2 \cdots v_n$, called a path from v_1 to v_n, denoted $p_{v_1v_n}$, where v_1 is called initial and v_n is terminal.
- Let $M_X = (V_X, E_X)$ be a manifold derived from a data set X. Given a path $p = v_1v_2 \cdots v_n$ in M_X, a trajectory t_p corresponding to p is a function of the sequence $t = t_1t_2 \cdots t_n$ where $t_i = m(v_i)$.
- Paths $p_1 = v_1v_2 \cdots v_n$ and $p_2 = w_1w_2 \cdots w_k$ where $w_1 = v_n$ can be concatenated to form a path $cat(p_1, p_2) = v_1v_2 \cdots v_nw_2 \cdots w_k$ from v_1 to w_k. Concatenated paths naturally have corresponding concatenated trajectories.
- Given a path $p = v_1v_2 \cdots v_n$, the reverse of p is the path $rev(p) = v_nv_{n-1} \cdots v_2v_1$ from v_n to v_1. Reversed paths naturally have corresponding reversed trajectories.
- A shortest path from v to w is a path $p = v \cdots w$ such that the order of p is less than or equal to the order of all other paths from v to w. The existence of a path $p = v \cdots w$ guarantees the existence of a shortest path from v to w.

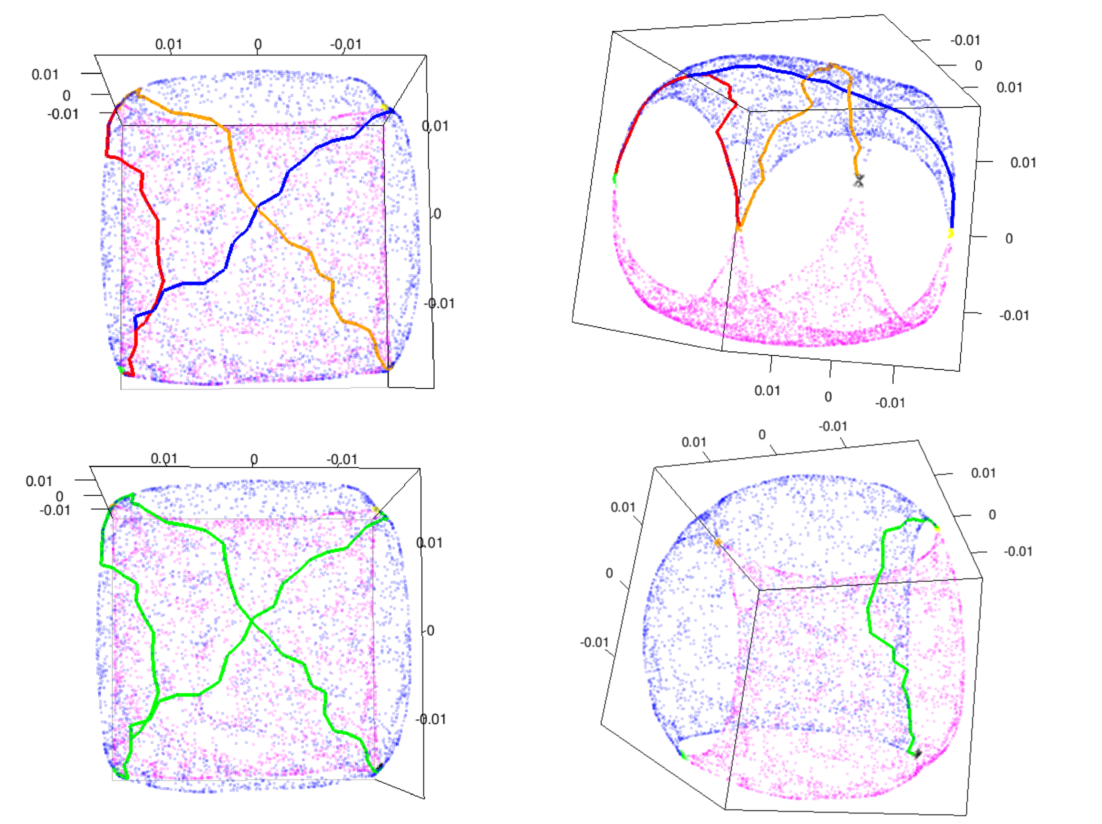
Paths and Trajectories in Generated Frames



1. Manifolds are formed over data sets Q_1 (magenta) and Q_2 (blue) in the manner described at left, and they are aligned using a set of pairs χ_{cor}, mapping Q_1 and Q_2 to a sets Q_1' and Q_2' in a new reference frame.
2. Manifolds $M_{Q_1'}$ and $M_{Q_2'}$ can then be formed over Q_1' an Q_2', and used to construct paths and corresponding trajectories connecting regions corresponding to χ_{cor}.

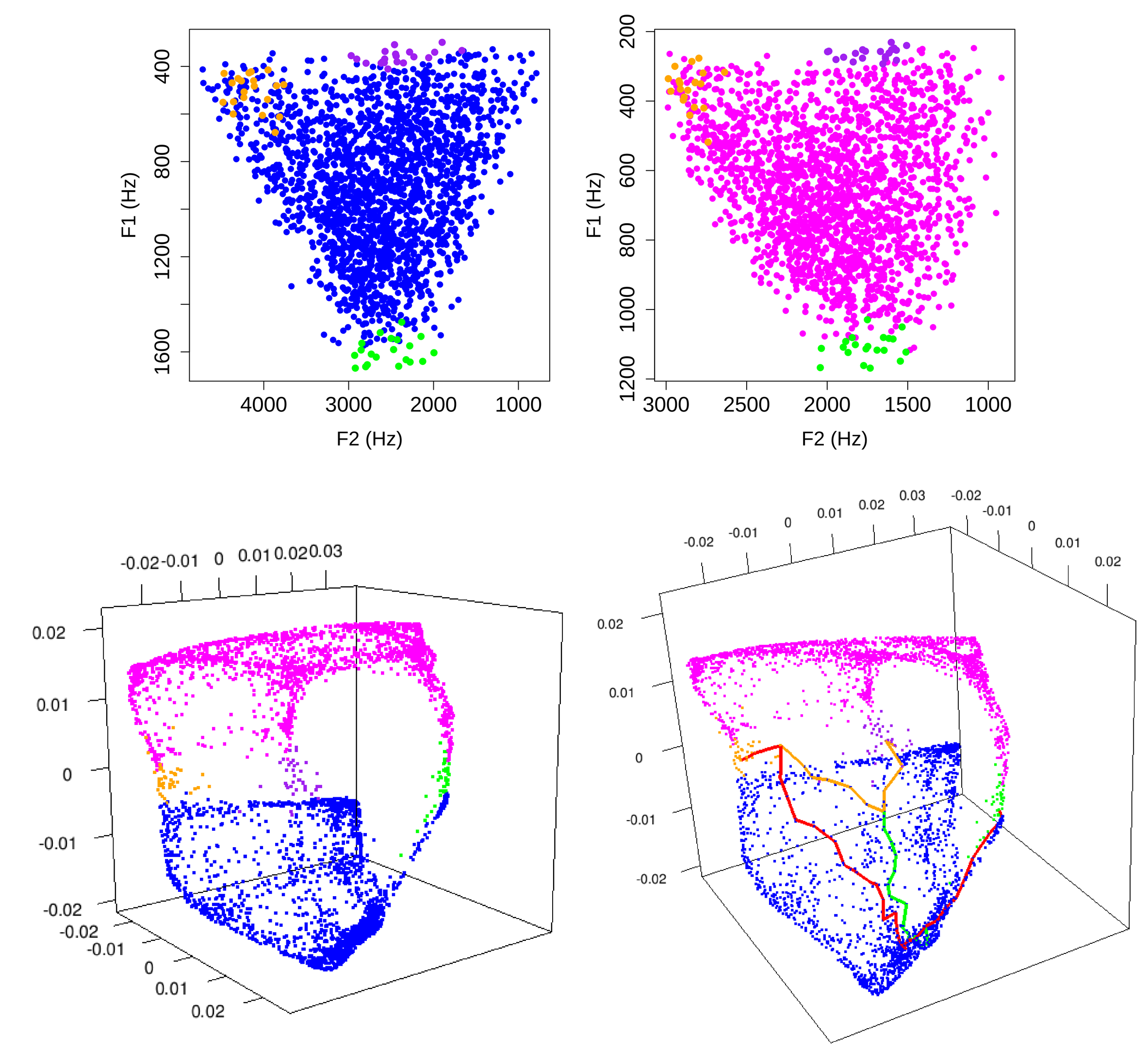


From Syntagmatic Paths to Paradigmatic Units



- Let $M_X = (V_X, E_X)$ be a manifold derived from a data set X. A target set $T \subseteq V_X$ is a collection of target vertices that have special significance, e.g., by corresponding to data in X coming from turn-taking vocal exchange.
- Let u and i be target vertices in T. A path p from u to i is called a syntagmatic path in M_X, and a trajectory t_p is a syntagmatic trajectory.
- The target subsequence of a path p from u to v in M_X, denoted $tar(p)$, is a subsequence of p composed of the target vertices in p.
- Let’s say that two target vertices u and i are separable iff there exist paths p_1 and p_2 such that u and i are the initial and terminal vertices of p_1 and p_2, respectively, and $tar(p_1) \neq tar(p_2)$.
- Let’s consider four target vertices u, i, o, and e, and suppose we have paths p_{ue} (traj. in orange), p_{io} (blue), and p_{ie} (red). We can form the path
$$p_{ueio} = cat(cat(p_{ue}, rev(p_{ie})), p_{io})$$
from u to o (green, bottom left).
- The path p_{ueio} guarantees the existence of a shortest path p_{uo}, and the nature of M_X ensures that u and o are separable, and each vertex in T is separable from each of the others.
- A set of target vertices T is a paradigmatic set if each vertex $v \in T$ is separable from every vertex in $T - \{v\}$. Each vertex in a paradigmatic set T is called a paradigmatic unit.

(Auditory-based) Commensuration Structures



- Given a set of socio-vocal data from turn-taking exchanges (top), together with a broad set of internalized vocal experience and internal representations of productions, an infant forms and aligns manifolds which generate representations for the creation of structures for the acquisition of vowel dynamics.
- To illustrate, we’ll simplify the picture a bit, and focus on the internalization of corner vowels [i], [a], and [u], and the formation of auditory manifolds formed over auditory representations corresponding to the infant’s internal representations.
- The infant aligns these manifolds using the internalized turn-taking experience, yielding (auditory-based) commensuration representations that are used to form a commensuration manifold.
- The turn-taking experience also yields the target regions for syntagmatic path construction through the commensuration manifold, which in turn yields the paradigmatic units that may enter into a phonology.

Discussion

- Much attention has been paid to computational models of phonological acquisition in recent decades, with renewed vigor in the subject seemingly occurring in concert with the promulgation of the latest algorithm/computation that catches the attention of funding agencies and other kingmakers.
- There is no reason to limit our view to what can be easily quantified and computed using popular computational methods when it is quite valuable to attempt to use an array of methods to bring within our view areas of inquiry that are scarcely recognized.
- At present, we are attempting to use a recent variation on the graphical model approach to shed light on the nature of the acquisition of cognitive structures for the representation of vowel dynamics, and its potential relations to an infant’s development of syntagmatic and paradigmatic systems of speech and language analysis.

Acknowledgments

We would like to thank Mary Beckman for helpful background discussion.

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