Manifold Alignment, Vocal Imitation, and the Perceptual Magnet Effect

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Introduction

Auditory representations differ

- People who have different vocal tracts have different vocalizations.
- Vocalizations of different talkers are represented differently even after applying auditory models (e.g., Moore et al., 1997) to a spectrum.

Computation of equivalence classes of representations

- Humans are able to impose equivalence classes over these differing representations, providing a basis for high-fidelity communication.
- This ability is apparent very early in infancy, demonstrated by the nature of the vocal exchanges between infants and their caretakers by four months of age (Masataka, 2003; Fitch, 2004, 2010).

Equivalence classes are language-specific, and interactively constructed

- The perceptual magnet effect (Kuhl, 1991; Guenther & Gjaja, 1996) suggests that computation of equivalence classes is sensitive to the ambient language.
- The influence of vocal imitation suggests that the equivalence classes are constructed via social interaction (Kuhl & Meltzoff, 1996; Masataka, 2003).

Objects and Aims

- We limit our inquiry to vowels, and take vowel normalization to be a cognitive process which yields equivalence classes of auditory representations of vowels.
- We briefly lay out a general approach to the theory of the acquisition of vowel normalization during infancy, along with a computational modeling framework.

Aspects of the Theory

Infant's construction of a model "self"

- An infant constructs/refines an internal model (Wolpert, Ghahramani, & Jordan, 1995) over articulatory and auditory representations.
- Construction of the self involves cross-modal abstraction over representations yielded by the distinct modalities (Davenport, 1976; Kuhl & Meltzoff, 1982).

Infant's construction of a model of "others" and alignment with the self

- Humans "trace patterns upon" their internal representations of the external world (Lippmann, 1922; on James, p. 16), which includes "other" humans.
- Relating the patterns imposed on other conspecifics to those imposed on the self enables "social learning" (as in Meltzoff's (2007) "like-me" framework).

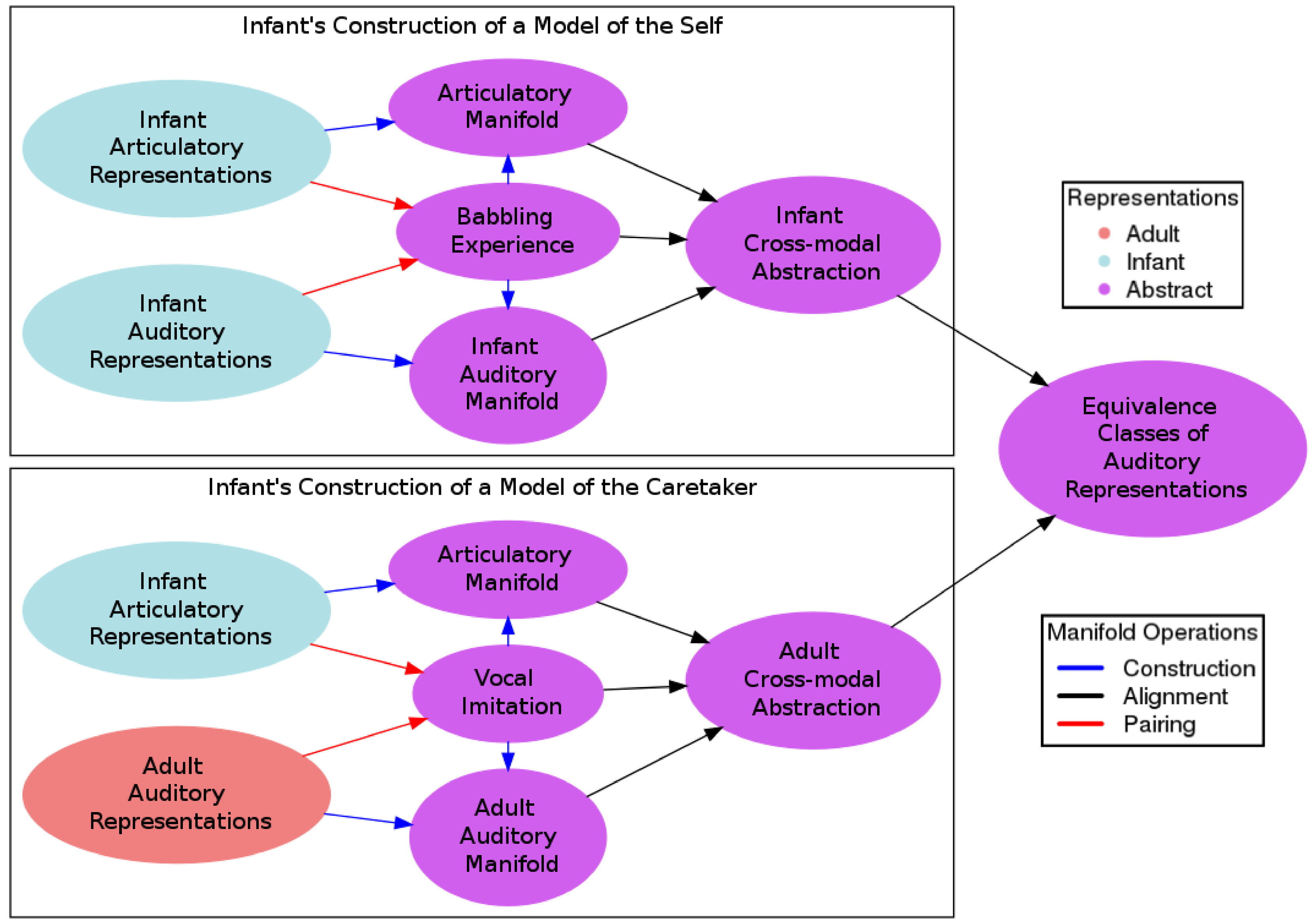
Infant's organization of sensory information using cognitive manifolds

- A cognitive manifold describes what our brains might know about something that is very complex and multi-dimensional by building a much lower-dimensional "map" of it.
- For example, a map of the world is a two-dimensional manifold built to describe what we need to know to navigate the three-dimensional surface of our planet.

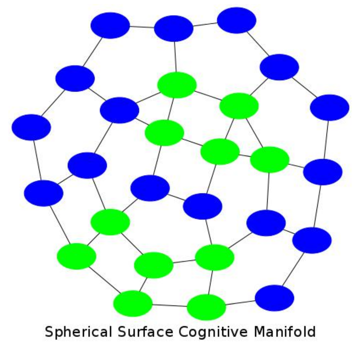
Key Theoretical Claims

- Infants construct cognitive manifolds – During the earliest stage of spoken language acquisition, infants construct cognitive manifold representations over their own vowel productions, and those of their caretakers.
- Vowel normalization is manifold alignment – The computation of equivalence classes of auditory representations of different talkers, including those of an infant learner, is the alignment of cognitive manifolds constructed by the infant.
- Vocal imitation guides alignment – The cognitive manifold alignment is guided by vocal imitative exchanges between infants and caretakers, with the perceptual magnet effect as a consequence of the exchanges.

System Architecture



Cognitive Manifolds



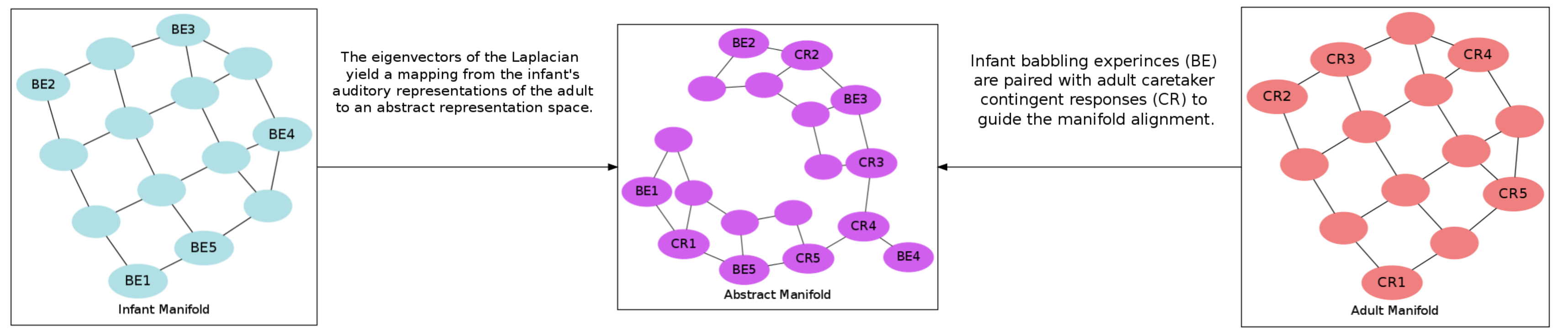
- Cognitive manifolds are weighted graphs whose nodes encode sensory info.
- Organizational aspects of the information is encoded in the weighted edges.
- Mappings on manifolds can be learned using their graph Laplacians, which are operators derived from edge weights.

Manifold Alignment: Perceptual Magnet Example

- Let E_I and E_A denote sets of infant and adult caretaker auditory representations and denote imitation pairing as $\chi_{im} : E_I \times E_A \to \{0, 1\}$. In the depiction below,

$$\chi_{im} = \{\langle BE1, CR1\rangle, \langle BE2, CR2\rangle, \langle BE3, CR3\rangle, \langle BE4, CR4\rangle, \langle BE5, CR5\rangle\}.$$

- The infant manifold $M(E_I)$ and adult manifold $M(E_A)$ are aligned (Ham et al., 2005) by combining their graph Laplacians, using the pairs χ_{im}.
- The alignment process yields mappings from $M(E_I)$ and $M(E_A)$ to a space of abstract representations of those in E_I and E_A such that the abstract representations of the points in each pair in χ_{im} are close to each other.



Expansion to Cross-modal Modeling

- Let A_I denote the set of infant articulatory representations corresponding to the infant auditory representations in E_I, and $M(A_I)$ an articulatory manifold.
- Denote cross-model pairing as $\chi_{cm} : E_I \times A_I \to \{0, 1\}$, and let

$$\chi_{cm} = \{\langle BE1, AR1\rangle, \langle BE2, AR2\rangle, \langle BE3, AR3\rangle, \langle BE4, AR4\rangle, \langle BE5, AR5\rangle\}.$$

- The infant constructs a model self by aligning $M(E_I)$ and $M(A_I)$, using the pairs χ_{cm}, mapping points in E_I and A_I to an abstract cross-modal space C_I.
- The infant constructs a model of the adult caretaker by aligning $M(E_A)$ and $M(A_I)$, using the pairs χ_{cm}, mapping points in E_A and A_I to an abstract cross-modal space C_A.
- Let $C_I(\mathbf{e}_I)$ denote the abstract representation of $\mathbf{e}_I \in E_I$, and $C_A(\mathbf{e}_A)$ that of $\mathbf{e}_A \in E_A$. Finally, $M(C_I)$ and $M(C_A)$ are aligned using the pairs

$$\chi_{abs} = \{\langle C_I(BEi), C_A(CRi)\rangle \mid i = 1, \ldots, 5\}.$$

Conclusions and Acknowledgments

- We have put forward a potentially useful conceptualization and computational framework for the investigation of vowel normalization in infants that incorporates a wide array of related phenomena.

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