A Dynamical Manifold Approach to Language Learning: Quantifying Cognitive Progress through Geometric Curvature

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Abstract

Language acquisition proceeds nonlinearly, marked by rapid progress, plateaus, and sudden breakthroughs. Traditional statistical and neural models cannot capture such evolving dynamics and cognitive effort over time. We propose a geometrical framework for modeling language learning as geodesic motion on a Riemannian manifold. Each coordinate axis represents a linguistic skill (e.g., vocabulary, syntax), and Ricci curvature quantifies cognitive resistance. Low curvature corresponds to fast learning, high curvature to plateaus, and negative curvature to moments of insight. The framework was tested through simulations and designed for empirical validation via fMRI studies and longitudinal learner data. Preliminary simulations demonstrate that curvature-based modeling successfully captures nonlinear transitions between learning regimes. Compared with Markov and neural network baselines, the model more accurately predicts the onset of plateaus breakthrough phases. Pilot fMRI data suggest positive correlations between curvature estimates and neural activity in Broca's area and the dorsolateral prefrontal cortex. Behavioral modeling further indicates superior predictive accuracy for plateau timing relative to benchmark approaches. This manifold-based approach offers interpretable, neurocognitively grounded insights into second-language acquisition. By linking curvature to cognitive load, the model accounts for plateaus and sudden insights while providing a foundation for adaptive tutoring systems and clinical applications in language disorder diagnostics.

Keywords: Language learning, Cognitive curvature, Plateau prediction

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