

A neural model for CDST: Resonance, attunement, and prosodic transfer in L2 development

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Abstract We employ the vocabulary of attractor states and coupled subsystems used by Complex Dynamic Systems Theory (CDST), offering a dynamical systems modelling account of how L2 prosody learning could take place at the neural level. Specifically, we propose a mechanism accounting for L1 prosodic attractor states constraining the perception of L2 prosody, with individual differences. Our perspective is based on Neural Resonance Theory, as a potential complement to CDST.

Keywords complex dynamic systems, L2 prosody, neural resonance theory, L2 development

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Wander Lowie's most productive provocations are as much methodological as theoretical. His work shows that variability is not "noise" to be filtered out but the engine of development, the signature of a self-organizing system in motion. Complex Dynamic Systems Theory (CDST), the framework Lowie pioneered with de Bot and Verspoor and mentioned in this issue (Lowie, 2026), introduces the vocabulary for this: attractor states, phase transitions, coupled subsystems competing and supporting each other's growth over time. In this contribution, we pursue what we see as a complimentary counterpart to CDST: a dynamical systems account of how L2 learning could take place at the neural level. We do this from the perspective of Neural Resonance Theory (NRT; Harding et al., 2025).

In L2 development, Lowie and colleagues have documented behavioral patterns consistent with CDST predictions, including attractor-governed trajectories, signatures of self-organization, and resistance to reorganization (De Bot et al., 2007; Lowie et al., 2014; Lowie & Verspoor, 2018). These dynamical systems features are inherent in NRT as well. We take up this connection in a domain Lowie's work has been moving toward: L2 prosody. While to our knowledge the formalized accounts of NRT are currently limited

to musical examples, speech prosody offers some immediate parallels to NRT accounts of musical pitch perception. We argue that this convergence accounts for one of the more stubborn puzzles CDST leaves open: why L1 prosodic attractor states so strongly constrain the perception of L2 prosody, and why some learners escape them more readily than others.

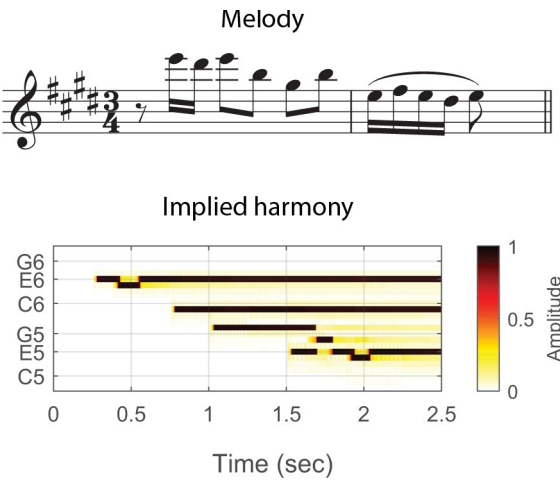
NRT has four components that are integral to the modelling technique that NRT uses to describe music cognition. Nonlinear neural resonance is the capacity of neurons to resonate, or oscillate, not only at the frequencies present in sensory input but also at harmonics, subharmonics, and complex interactions among frequencies. Attunement is the plasticity mechanism: patterns encountered more often strengthen the synaptic connections among neurons that resonate at those related frequencies, gradually reshaping the architecture of the oscillatory network. Strong anticipation means the dynamical system accounts for perception from input to output without positing an intermediate representational layer – so the system's percept is the resonance itself, not an internal representation of it. Dynamical stability is a concept inherent to physics; frequency ratios that are more stable are those that have lower, or simpler, integer ratios, meaning that some patterns are inherently easier to perceive than others. We focus on attunement and dynamical stability, as these two principles most directly illuminate the asymmetries between L1 and L2 prosody perception.

A Western-trained musician hearing a melody not only perceives the notes being played (Tramo et al., 2001), but an extensive neural network corresponding to the melody's underlying tonality resonates spontaneously, because years of training and exposure have attuned those frequency relationships to each other within the neural network (Figure 1; Kim, 2017). This is based both on frequency interactions themselves, because simple harmonic ratios easily resonate together, and on the strong synaptic connections formed during musical training. Trained musicians from a different musical culture, say traditional Turkish folk musicians, may listen to the same Western melody and have a different pattern of activated resonance frequencies that reflect their training of non-Western tonal relationships. The same logic extends to L1 prosody.

From the perspective of attunement, native language exposure does not merely familiarize a listener with certain f_0 prosodic patterns; it physically reshapes the oscillatory network through repeated co-activation, strengthening connections among neurons that resonate together at the frequencies that carry prosodic meaning in that language. So when a Dutch speaker hears an utterance begin on a particular f_0 , the oscillatory networks attuned to prosodic emphasis in Dutch begin to resonate – not because they are somehow present “in” the signal, but because attunement has made them part of the listener's oscillatory architecture. When a listener from a different L1 background encounters the same Dutch utterance, a network with a different resonance response may emerge, shaped by differing L1 frequencies of prosodic emphasis.

Accordingly, there is a robust and deeply entrenched attractor for L1 prosodic patterns. Thus, listeners absorb considerable f_0 variation and still perceive it as the intended con-

Figure 1 For an unaccompanied Western melody (top), neural resonance models show activated resonance frequencies (dark lines) at the underlying harmonic structure of the melody. A similar underlying resonance structure may be emerging for speech prosody, that is strongest for L1 patterns. Adapted from Kim (2017), *Frontiers in Psychology*, licensed under CC BY 4.0



trast because the system has been pulling toward that pattern their whole lives. This is what makes L1 prosodic perception robust – and what makes the L1 network so resistant to reorganization when the learner encounters L2 input.

Coupling strength is the degree to which populations of oscillators synchronize with each other and in modelling, a proxy for overall efficiency in neural communication. Higher coupling strength of the individual would mean that they can more easily hold stable resonance patterns that have a narrower attractor space and are less dynamically stable. Thus, new patterns that are missing a supportive neural architecture could more easily elicit a resonance percept in individuals with higher coupling strength.

In music, performers with high coupling strength and extensive training hold complex interval ratios that others cannot. A performer specialized in Schoenberg’s atonal movement develops sensitivity and steadiness when executing dissonant melodies, while an amateur performer may derail, perhaps resolving toward simpler consonant intervals when distracted or playing a piece for the first time – and land on the nearest stable attractor. The analogy for language is direct. Some L2 learners (like those with early multilingual prosodic exposure, or with naturally higher coupling strength) may more readily embody resonance patterns that diverge from their L1 network, tuning into the L2 attractor rather than defaulting to the deeper, more familiar L1 one. Even after years

of living in the Netherlands, one coauthor still defaults to English focus prosody when speaking Dutch under any real communicative pressure – the L1 attractor, apparently, does not yield to good intentions ... or prolonged residence.

How would one go about testing this? The NRT neural network models offer a tractable path. Perform a dynamical systems analysis on a large corpora of speech prosody data to understand the attractor landscapes of L1 prosodic focus pitch intervals. Train the model on utterances with contrastive focus prosody and manipulate the coupling strength parameter. Then check: Do the L2 patterns that are learned first, have inherently more dynamical stability or do they more closely match to the attractor space of L1 architecture? If the coupling parameter is increased or decreased, does the emergence of L2 prosody perception match the data of populations known to respectively differ in this regard (musicians versus non-musicians, or early versus late bilinguals)?

N1 amplitude (the auditory event-related potential that tracks pitch onset) is a plausible neurophysiological correlate for the experimental side of this work: sensitive to pitch processing, modulated by attentional state, and available in paradigms that permit direct comparison between L1 and L2 prosodic stimuli. However, when implementing NRT in language-domain paradigms, we can immediately think of two caveats. First, the NRT model was developed for music perception; the parameter space for speech may differ substantially, and optimizing it for prosodic tracking will require dedicated research. Second, adapting the model for speech may require different consideration for the temporal dynamics of pitch (not only which frequencies occur, but when and at what amplitude). For example, the temporal development of prosodic contour in delta and theta bands is suggested to modulate phonological processing through phase-amplitude coupling (Giraud and Poeppel, 2012), which might in turn have implications for f_0 pitch perception. These are not objections; to the contrary, they are open questions that could help to define a research agenda.

The puzzle this framework is designed to address is not just hypothetical. In a lexical stress identification study with native Dutch learners of English, Everhardt et al. (2024) found that listeners applied their L1 cue-weighting strategy in the L2: They relied on f_0 contour as the primary stress cue in English, despite vowel quality being the more informative cue in that language. More tellingly, their sensitivity to f_0 contour changes was greater in Dutch than in English even when the acoustic f_0 differences between the two stimulus sets were held constant. The signal did not differ. It was instead the listener's neural history with it that differed.

Adults showed stronger f_0 sensitivity than adolescents across both languages. This is consistent with the deepening of prosodic attractor states through continued exposure. What is more, these patterns held even under spectro-temporal degradation: when f_0 was rendered less perceptible via cochlear implant simulation, listeners did not re-weight toward the more perceptible vowel quality cue in either language (see Verkhodanova et al., this issue, for further discussion). The L1-dominant strategy persisted under perturbation. Cue-weighting theory describes these findings but does not account for their neural

basis: why attunement deepens with age, why L1 networks fire preferentially for matched acoustic input, and why the system resists reorganization even when its preferred cue is compromised. NRT provides that account.

That the oscillatory infrastructure NRT identifies in music also operates in speech has been demonstrated empirically. Harding et al. (2019) recorded EEG from participants with varying degrees of musical training as they listened to melodies and sentences with matched rhythmic structure, measuring cerebral-acoustic coherence as an index of cortical entrainment neural activity phase-locked to rhythmic structure across both domains, supporting the domain-generalty of the entrainment mechanism. The training asymmetry that emerged, however, is directly relevant: highly trained musicians showed stronger cortical tracking of musical rhythm than of speech rhythm, as years of musical exposure had strengthened domain-specific oscillatory coupling via the attunement NRT predicts. The speech entrainment response, by contrast, did not scale with musical training. It remained stable across training levels. This asymmetry is our analogy. L1 prosodic exposure does for speech what musical training does for music: it deepens attractors in the oscillatory networks that track f_0 contour and phrasal structure, making those networks preferentially responsive to familiar patterns.

What we have proposed here is not a replacement for CDST but a possible extension of it, one that trades the phenomenological vocabulary of attractor landscapes for dynamical systems modelling of oscillatory patterns, from which hypotheses about perception and learning can be derived. The verification path is tractable (operationalized via language-domain state space parameters, coupling strength parameters, contrastive focus training sets, and N1 amplitude as a neural index) and the individual differences prediction is falsifiable. What remains is to do the work. Wander, are you sure you want to retire?

Personal note

Wander, it has been a pleasure co-supervising PhD students with you these last six years. You give an aspirational example of gentle leadership and wisdom. I also find you to be an engaging lecturer and to have much breadth in your methodological knowledge. It seems like we only just started collaborating – sorry that you are leaving so soon! Best wishes for your retirement. – Eleanor Harding

I had the honor of co-supervising my first RUG PhD with you around a decade ago and can't think of anyone better to usher me into the joys of this kind of collaboration. The way you balance scholarship and kindness, especially with doctoral students, is one of the many reasons I hold you in such high esteem. It is my pleasure to consider you not only a colleague but a mentor. Enjoy this next chapter! – Matt Coler

Author contributions

Eleanor Harding: conceptualization, writing – original draft, review and editing; Matt Coler: conceptualization, writing – review and editing.

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Statement of technology use

No AI-based generative technology was used in the preparation of this manuscript and the execution of the research that the manuscript reports upon.

Supporting information

None.

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