Bouncing the Network: A Dynamical Systems Model of Auditory-Vestibular Interactions Underlying Infants’ Perception of Musical Rhythm

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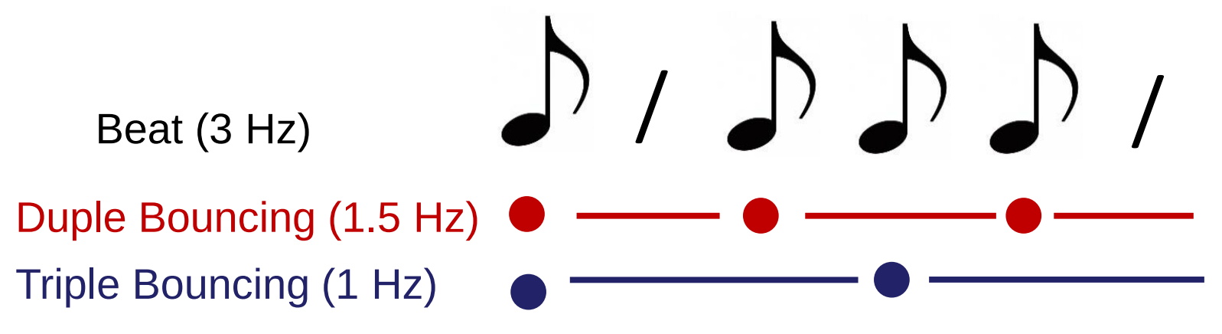
Background

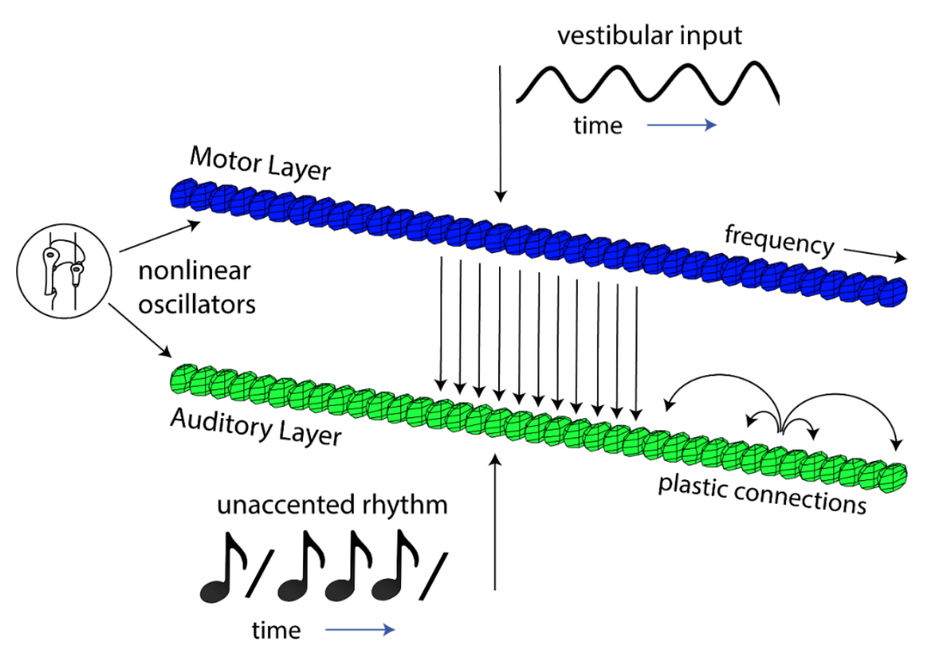
Previous work suggests that auditory-vestibular interactions, which emerge during bodily movement to music, can influence the perception of musical structure, such as the perception of accented beats in musical rhythm[1-3]. In a seminal study on the development of musical rhythm, Phillips-Silver & Trainor (2005) found that periodic, maternal bouncing of 7-month-old infants to an unaccented rhythm influenced infants' listening preferences for accented rhythms that matched the rate of maternal bouncing, suggesting that auditory-vestibular interactions shape rhythm perception in infancy. Expanding a recent theoretical model of infant rhythm perception[4], in the current study, we propose a dynamical systems model of auditory-vestibular interactions thought to underlie infants’ listening preferences for accented rhythms. The model, featuring two neural networks of non-linear oscillators to represent developmentally nascent auditory and motor systems, was used to simulate the effect of maternal bouncing (e.g., vestibular input) on infants' listening preferences for duple- and triple-accented rhythms. First, we demonstrate that simultaneous auditory-vestibular training shaped the model’s response to musical rhythm online, enhancing vestibular-related frequencies in the model’s oscillatory activity. Next, we demonstrate that simultaneous auditory-vestibular training, relative to models that received auditory- or vestibular-only training, facilitated neural plasticity, producing stronger connections between network oscillators during a period of unsupervised learning. Finally, we show that models which received simultaneous auditory-vestibular training, but not models that received auditory-only or vestibular-only training, “preferred” rhythmic frequencies related to their “bouncing,” resonating more strongly at frequencies related to the combined auditory-vestibular stimulation. This finding is qualitatively similar to infants' preferences for accented rhythms that matched the rate of maternal bouncing to an unaccented rhythm.



Phillips-Silver & Trainor, 2005

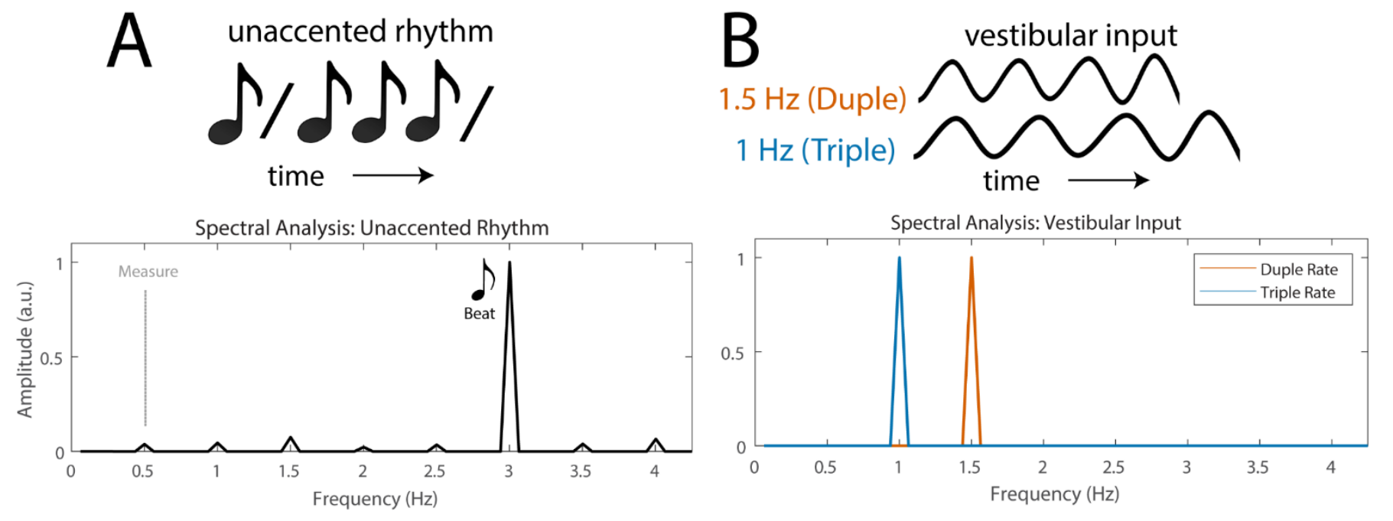
Methods

Model Architecture



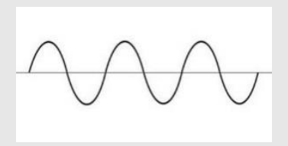
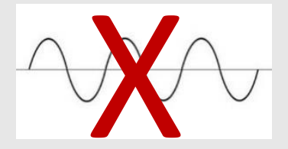
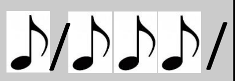
- Two multi-frequency oscillatory neural networks with a Hebbian plasticity rule.

Stimulus Array



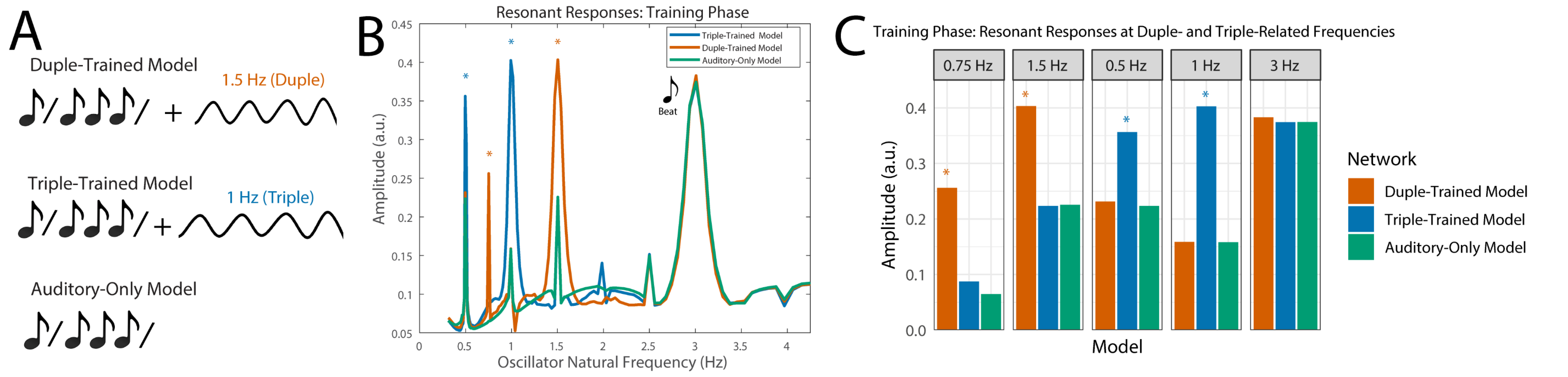
- Notation and frequency-domain representations of the (A) Unaccented Rhythm (B) and Duple- and Triple-Rate Maternal Bouncing (i.e., Sinusoidal Forcing).

Training and Test Procedures

Network	Training Phase	Test Phase
Auditory Network		
Motor Network		

Training Regimes

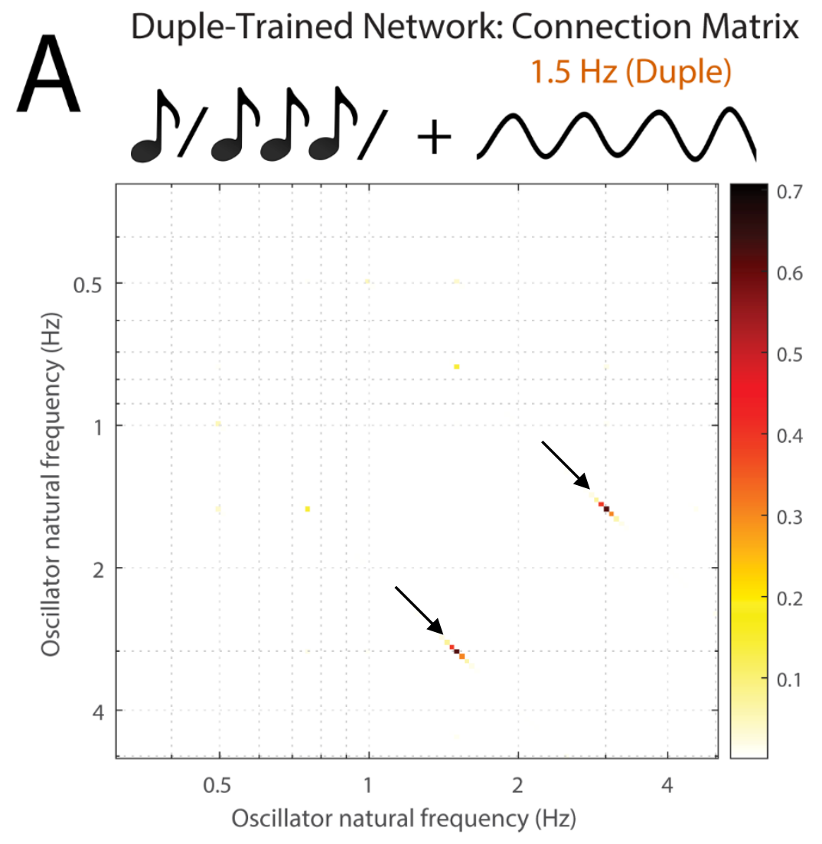
Model: Training	Auditory Training	Vestibular Training
Duple-trained model	X	X
Triple-trained model	X	X
Auditory-only model	X	-
Duple-only model	-	X
Triple-only model	-	X

Vestibular Input Shapes the Neural Response to Musical Rhythm

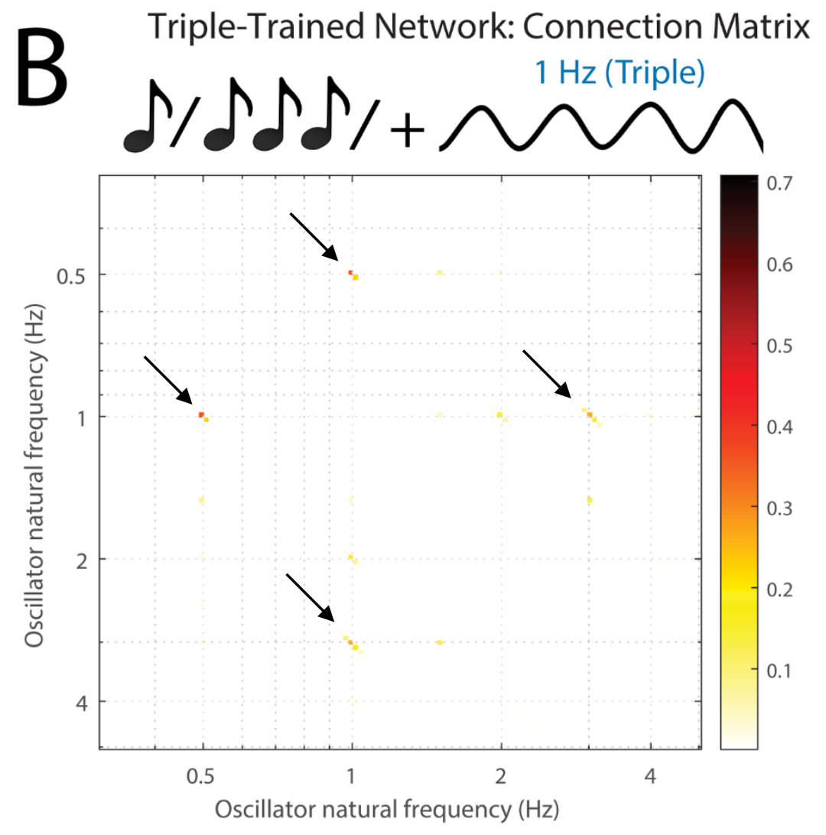


(A) Training stimuli for the duple-trained, triple-trained, and auditory-only models. **(B)** Resonant responses in the auditory network of the duple-trained (red), triple-trained (blue), and auditory-only (green) models during the final half of the training procedure. **(C)** Resonant-response amplitude values that were extracted from the resonant responses in the duple-trained (red), triple-trained (blue), and auditory-only (green) models for duple-related (0.75, 1.5 Hz, marked with red asterisks), triple-related (0.5, 1 Hz, marked with blue asterisks), and the beat frequency (3 Hz). Here, the duple-trained model produced larger responses at duple-related frequencies (0.75, 1.5 Hz) relative to the other models, while the triple-trained models produced larger responses at triple-related frequencies (0.5, 1 Hz) relative to the other models, suggesting that simultaneous auditory-vestibular training enhanced oscillatory responses to musical rhythm specifically at frequencies (i.e., harmonic and subharmonic frequencies) related to the rate of vestibular input.

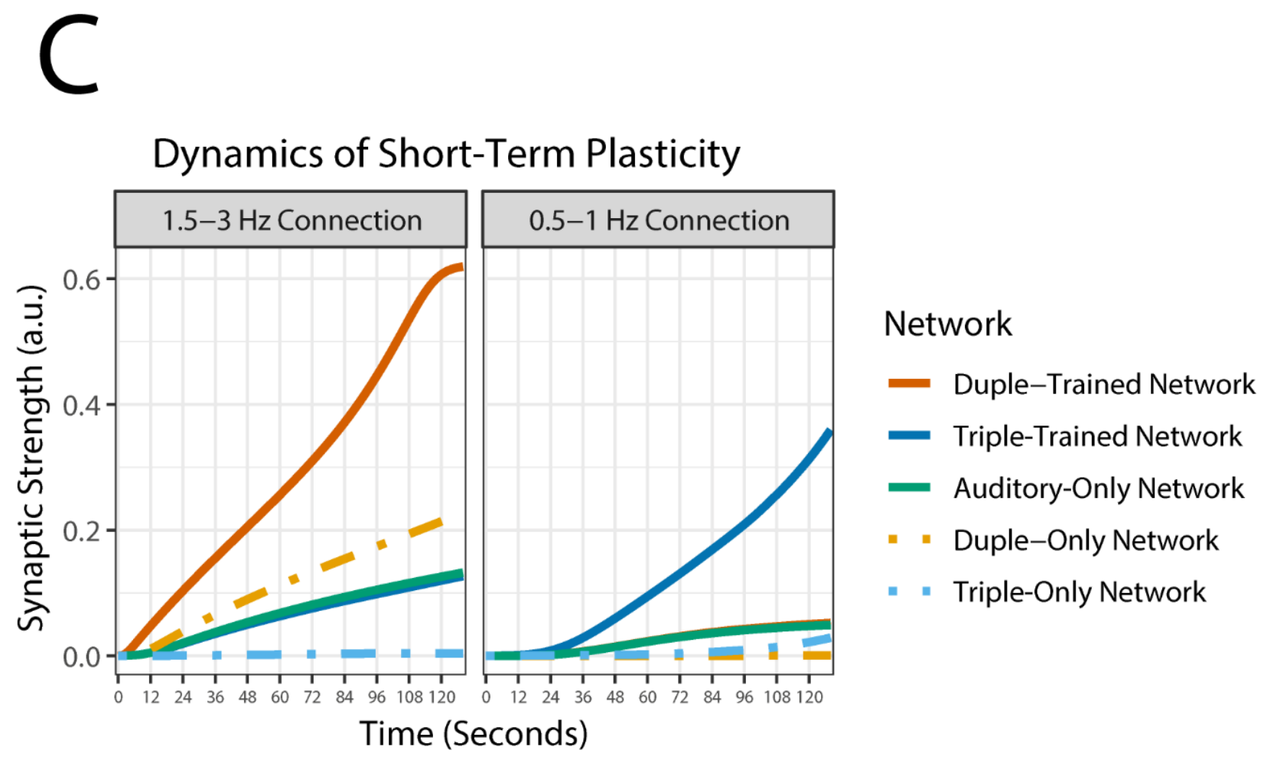
Auditory-Vestibular Training Facilitates Neural Plasticity



A. Connection matrix of the duple-trained model. The duple-trained model, which was trained on an unaccented rhythm and duple-rate vestibular input, learned strong, bi-directional connections between 1.5 – 3 Hz.

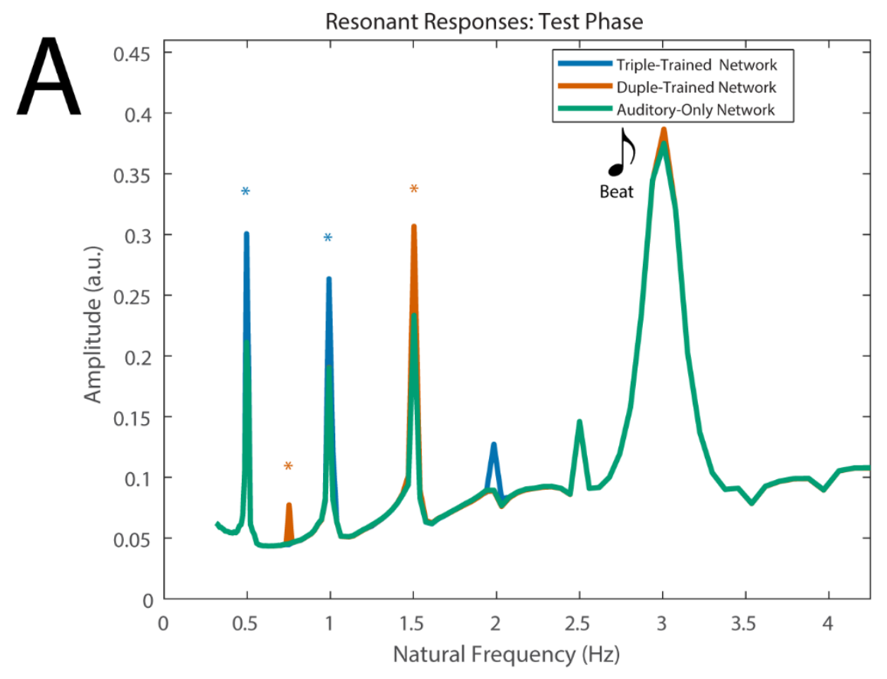


B. Connection matrix of the triple-trained model. The triple-trained model, a model trained on an unaccented rhythm and triple-rate vestibular input, exhibited more distributed learning, with bi-directional connections emerging between 0.5 – 1 Hz and 1 – 3 Hz

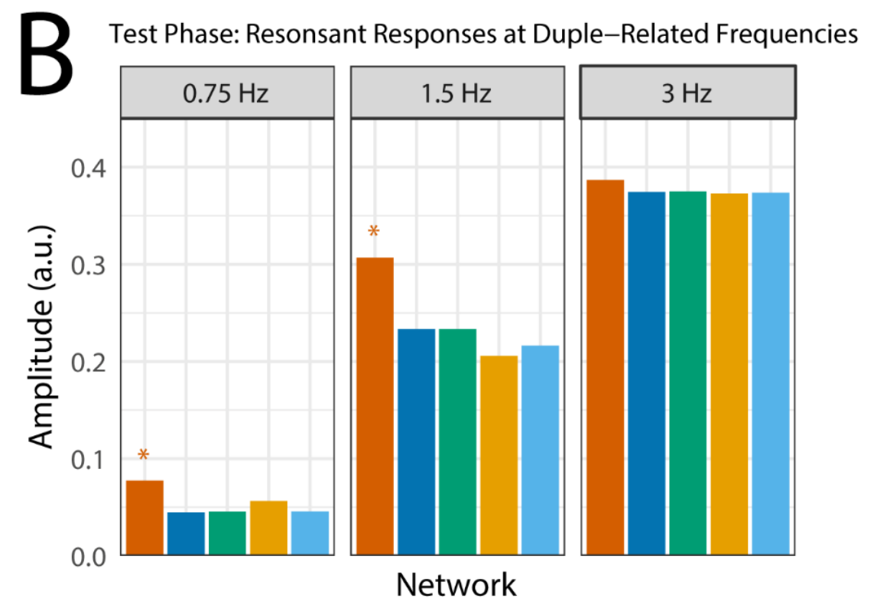


C. The time-course of learning plastic connections at the strongest duple-related frequencies (1.5 – 3 Hz) and triple-related frequencies (0.5 – 1 Hz). **(C, Left)** The synaptic connection between network oscillators at 1.5 and 3 Hz, the strongest duple-related connection, as a function of training time. **(C, Right)** The synaptic connection between network oscillators at 0.5 and 1 Hz, the strongest triple-related connection, as a function of training time.

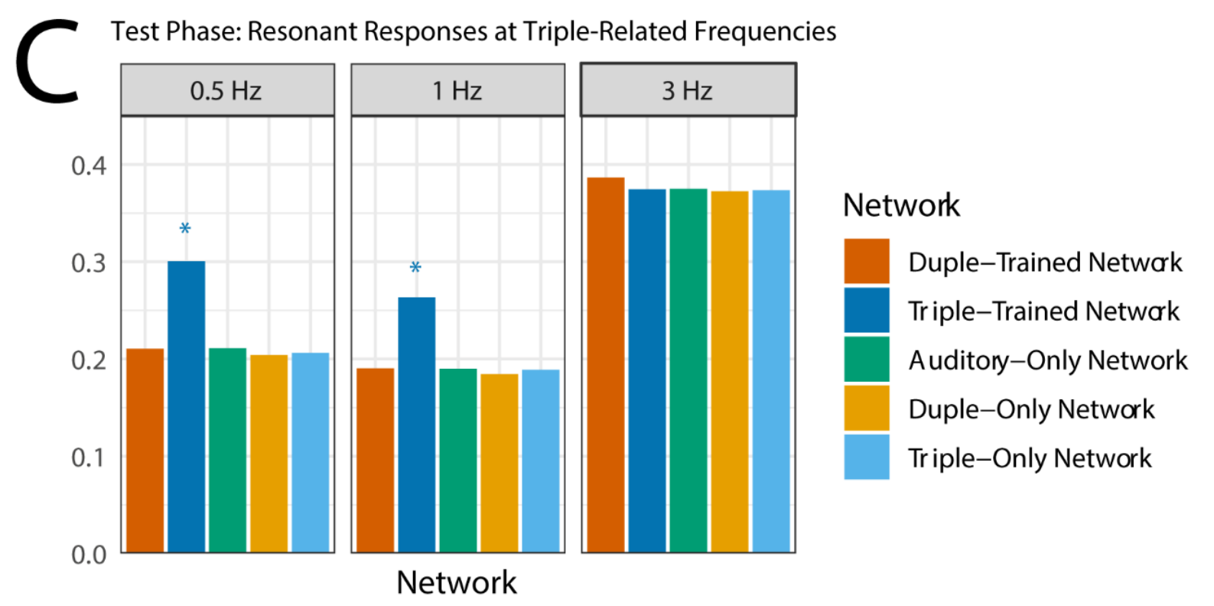
Auditory-Vestibular Models Preferred Vestibular-Related Rhythmic Frequencies



A. Resonant responses (i.e., average oscillatory activity) for the duple-trained (red), triple-trained (blue), and auditory-only (green) models during the final half of the test procedure. Here, the duple- and triple-trained models resonated strongly at frequencies related to the vestibular training in response to the unaccented rhythm.



B. Resonant-response amplitude values for all models for duple-related frequencies during the test phase. Here, the duple-trained model produced the largest resonant responses at duple-related frequencies (0.75, 1.5 Hz) in response to the unaccented rhythm during the test phase.



C. Resonant-response amplitude values for all models for triple-related frequencies during the test phase. Here, the triple-trained model produced the largest resonant responses at triple-related frequencies (0.5, 1 Hz) in response to the unaccented rhythm during the test phase.

Summary and Interpretations

- Auditory-vestibular training shaped the neural response to musical rhythm, enhancing oscillatory activity at vestibular-related frequencies.
- Auditory-vestibular training facilitated neural plasticity, producing stronger connections between oscillators, relative to auditory- or vestibular-only training.
- Auditory-vestibular training engendered a preference in the model for vestibular-related rhythmic frequencies:
  - Similar to infants’ preference for accented rhythms that matched the rate of maternal bouncing (Phillips-Silver & Trainor, 2005).

Future Directions

- Towards a general framework of rhythm development using Neural Resonance Theory[4,5].
  - Model the effects of short- and long-term training on rhythm perception-action[6]
  - Model tempo preferences across the lifespan[7]
  - Implement multiple timescales of learning into the model

References

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4. Tichko, P., & Large, E. W. (2019). Modeling infants’ perceptual narrowing to musical rhythms: neural oscillation and Hebbian plasticity. *Annals of the New York Academy of Sciences*, *1453*(1), 125–139.
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7. Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition*, *77*(3), 251–288.

Model Equations

$$\text{(1a)}\quad \tau_{1i}\dot{z}_{1i} = \underbrace{z_{1i}\left(\alpha + i2\pi + \beta_1|z_{1i}|^2 + \frac{\beta_2|z_{1i}|^4}{1-|z_{1i}|^2}\right)}_{\text{Intrinsic Dynamics}} + \underbrace{x(t) + \sum_{j\neq i} c_{ij} z_{1j}^{k_{ij}} \bar{z}_{1i}^{m_{ij}-1} + \sum_j d_{ij}\frac{z_{2j}}{1-z_{2j}}\cdot\frac{1}{1-\bar{z}_{2j}}\cdot\frac{1}{1-\bar{z}_{1i}}}_{\text{Time-Varying Input and Oscillator Connections}}$$

$$\text{(1b)}\quad \tau_{2i}\dot{z}_{2i} = z_{2i}\left(\alpha + i2\pi + \beta_1|z_{2i}|^2 + \frac{\beta_2|z_{2i}|^4}{1-|z_{2i}|^2}\right) + y(t)$$

Equations (1a, 1b) describe the dynamics of neural oscillators in the auditory (1a) and motor networks (1b). Here, z_{1i} and z_{2i} are complex-valued state variables whose real part represents the excitatory activity and whose imaginary part represents the inhibitory activity of the i^{th} neural oscillator in the auditory network, 1, and motor network, 2, respectively. The natural frequencies of the i^{th} oscillator in the auditory network, 1, and motor network, 2, is given by $f_{1i} = 1/\tau_{1i}$ and $f_{2i} = 1/\tau_{2i}$, respectively. When $\beta_1 < 0$, the endogenous activity of network oscillators is governed by the α parameter, where $\alpha_c = 0$ is the critical point. For $\alpha < 0$, the network oscillators will exhibit damped oscillation, while for $\alpha > 0$, the network oscillators will spontaneously oscillate via an Andronov-Hopf bifurcation. The βs reflect nonlinear damping parameters. Finally, c_{ij} represents input from the synaptic connection between the *j*th oscillator to the *i*th oscillator in the auditory network that are in a mode-locked relationship (i.e., *k*:*m* integer-ratio relationships), while d_{ij} represents oscillatory input from efferent connections that connect the motor network to the auditory network. $x(t)$ and $y(t)$ are time-varying inputs to the auditory and motor network, which reflect a musical rhythm and maternal bouncing, respectively.

$$\text{(2)}\quad \underbrace{\tau\dot{c}_{ij} = c_{ij}\left(\lambda_1 + \mu_1|c_{ij}|^2 + \frac{\epsilon_c\mu_2|c_{ij}|^4}{1-\epsilon_c|c_{ij}|^2}\right) + \kappa\sqrt{\epsilon_c}^{\,k_{ij}+m_{ij}-2}\, z_i^{m_{ij}}\bar{z}_j^{k_{ij}}}_{\text{Hebbian Learning Dynamics Between Mode-Locked Oscillators}}$$

Equation (2) describes the dynamics of Hebbian learning in the auditory network of the model. Here, c_{ij} is a complex variable that represents the amplitude and phase of the synaptic connection between the *j*th and *i*th oscillator in the auditory network. The parameters λ, $\mu 1$, $\mu 2$, κ, and ϵ_c determine the dynamics of the plasticity for oscillators that are near resonant frequency relationships, $m_{ij}f_i = k_{ij}f_i$. The unsubscripted t represents the global learning timescale. We set t to a small value (i.e., faster timescale) to simulate short-term plasticity thought to arise from auditory-vestibular training.