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Finding the Groove in Neural Space

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Introduction: A fundamental component of coordinated periodic movements is **rhythm**. From locomotive actions, such as walking or reaching, to more complex actions, such as dancing or playing an instrument, periodic movements require precise synchronization. Although substantial research has explored the neural underpinnings of broad cyclic movements like locomotion in preclinical models [1-3], it remains unclear how rhythms are represented, especially in humans, and what role sensory feedback plays in generating and maintaining rhythms.

Materials, Methods, and Results: In this study, we investigated the neural representations underlying rhythmic hand movements in the human sensorimotor cortex of participants with intracortical implants in the primary somatosensory (S1) and motor (M1) cortices. We sought to understand how M1 encodes rhythm and characterizes the dynamics of this encoding at both the single-neuron and population levels. Participants were instructed to tap their index finger in tandem with an auditory cue presented at different tempos. In the first experiments, participants were presented with both distinct groups of tempos and a continuous range of tempos. In the second experiment, participants performed a similar tapping task but on some trials did not tap a surface and instead tapped with their hand freely, removing sensory feedback. Finally, we asked participants to continue tapping with the same tempo after the cessation of the auditory cue.
At the single-neuron level, we found signatures of entrainment and identified subsets of neurons across M1 and S1 that were phase-locked, frequency-tuned, both, or neither. Examining the population, we identified a low-dimensional representation, or manifold, in neural state space that displayed frequency-dependent rotational dynamics. Within this manifold, oscillations (one per tap) existed along a tempo axis. We quantified the geometry of this manifold by calculating the trajectory speed and diameter of the individual rotations. We found that the geometry and location of these rotations in state space were highly variable during the initial taps of a trial, but became more stable over time as the *groove* was found. This transition functionally distinguished an establishment period from a maintenance period. Lastly, although we observed these rotations in the absence of tactile feedback or auditory cues, the organization of them never fully stabilized, particularly in the absence of tactile feedback, suggesting that the groove was never established.

Conclusion: In this study, we demonstrated that single-neuron activity in the human sensorimotor cortex exhibits signatures of rhythmic entrainment. More importantly, we showed that population activity contains frequency-dependent rotational dynamics that govern the entrainment and maintenance of rhythmic hand movements. However, these dynamics struggled to find the *groove* in the absence of sensory feedback. Future experiments will explore more complex rhythms, such as syncopation.

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