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# **NEST** 2019 ABSTRACTS

# What happens when musicians attempt to desynchronize gradually? Dynamics of interpersonal coordination in the performance of Steve Reich's *Drumming*

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At the last year's New England Sequencing and Timing meeting, Michael Schutz presented performance data for Steve Reich's *Drumming* (1971). Two of the world's leading percussionists, Russell Hartenberger and Bob Becker, recorded a section from *Drumming* in the naturalistic environment of the LIVE Lab at McMaster University. The score calls for two musicians playing identical rhythmic patterns to start in synchrony and then gradually desynchronize by one of them speeding up slightly while the other holding a constant tempo—a process called phasing. An analysis of the performance data showed that contrary to their intentions, both musicians sped up and slowed down together in the course of phasing. A dynamic visualization of these complex interactions is available at https://maplelab.net/reich/.

Here we present a dynamical systems explanation for the non-monotonic trajectories in the performance data. Some alignments of rhythmic patterns, such as a unison and interlocking patterns, are attractors in interpersonal coordination. They can be played effortlessly compared to other random alignments, and musicians are drawn back to them involuntarily when their coordination is perturbed. Phasing can be considered as traveling a phase space through multiple attractors. The acceleration of both musicians observed when they began to desynchronize indicates an attraction back to synchronization. The deceleration observed when they approach a stable interlocking pattern reflects a relaxation towards a new attractor.

To test this idea, we first analyze the performance data further to examine the relative phase of two musicians at the beat level and the cycle level. We modeled the attractor dynamics in phasing performance with two coupled oscillators, one with a fixed natural frequency and the other with an adaptive frequency controlled by the targeted phase difference at the cycle level. The instantaneous frequencies of the oscillators showed a pattern of acceleration and deceleration as found in the human performance data. Thus, the model successfully captured the dynamical interaction between the artistic intention of phasing and the obligatory tendency of interpersonal synchronization.

# The relative phase of bimanual rhythmic tapping exhibits preference for simple ratios

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The provenance of musical structures such as pitch, harmony and evenly spaced metric subdivisions is an oft-debated question. With respect to rhythm and meter, dynamic accounts based on the formal constraints or geometry involved in synchronizing periodic movements predict that not all phases are born equal. For example, coordination is more difficult for anti-phase than in-phase. Anti-phase is where one effector completes a cycle when the other is at its half way point (1/2) of its cycle. Music typically has richer structures than simple in- and anti-phase relations. Here we investigated the dynamic properties of bimanual synchronization at other phases, such as one hand tapping at the quarter (1/4) of the cycle of the other hand, or the third (1/3), to two fifths (2/5), etc. We instructed participants (*N*=12) to maintain different phase relations of bimanual tapping while performing a synchronization-continuation task. Each trial started with phased auditory cues for each hand. After cuing discontinued, participants' task was to maintain the same phase while increasing the tapping rate. Thus, we probed the stability of different initial phases because, as expected, increasing the rate of tapping leads to increased variability and eventually to a transition to in-phase tapping. Importantly, the instructed phases were sampled from a theoretic hierarchy of ratio complexity, the Stern-Brocot tree, generating ratios in the range from 0/1 (in-phase) to 1/2 (anti- phase). We found that coordination stability across trials was accounted for by the hierarchical model of ratio complexity better than by the absolute distance to in- and anti-phase or by the asynchrony. Thus, the ease with which people can maintain a bimanual pattern of tapping can be explained by the theoretical complexity of the temporal relationship, providing further insight in how rhythm and meter in music are constrained by synchronization dynamics.

## Covert motor activity and auditory rhythm perception

Ross, J.M., Iversen, J.R., Makeig, S., & Balasubramaniam, R.

Neural systems supporting body movement are active during music listening, even in the absence of overt movement, but this covert motor activity during music processing is not well understood. First, we present an EEG study comparing neural signatures of movement control and of passive music listening. This work is the first to study music-related mu modulation in the absence of overt movement and the first to source-resolve mu during music listening. Our results suggest topographically organized motor inhibition during music listening. I then discuss claims that covert motor activity may be used in auditory timing prediction, and present evidence in support of this view from our work with a causal transcranial magnetic brain stimulation design. These data support that motor networks can play an essential role in musical timing perception. Taken together, these studies support a close relationship between overt and covert motor activity, and between covert motor activity and auditory timing perception.

# American listeners perceive culturally unfamiliar music as faster than culturally familiar music, regardless of actual tempo

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Listeners perceive foreign speech as spoken faster than native speech even if there is no difference in the rate of sound, a phenomenon called the 'Gabbling Foreigner Illusion'. Similarly, studies have found that people tap at lower (faster) metrical levels to culturally unfamiliar music than familiar music. Cultural-specific experience may be necessary for listeners to perceive larger structures that unfold at a slower rate (sentences or phrases), which may lead them to focus on the rapidly changing surface of speech or music, giving rise to the illusory impression that unfamiliar speech or music is faster. We conducted two studies to ask whether listeners perceive the tempo of culturally unfamiliar and familiar music differently, by presenting English-speaking listeners from the USA with wordless excerpts of commercial pop music from multiple cultures (West African, American/British, Indian, Turkish, and Latin American). Participants heard pairs of musical excerpts and indicated if the tempo of the second clip was slower, the same, or faster than the first clip. In one experimental condition, participants made ratings after listening passively and in the other condition they made ratings after tapping along to each excerpt. In both conditions, listeners' tempo ratings were more accurate when there were no culture changes between clips in a pair. When presented with a clip of culturally familiar American/British music paired with a clip from another unfamiliar musical culture, participants always rated the American/British clip as slower, regardless of the actual relative tempo of the clip. These data suggest that, at least for listeners from the United States, cultural familiarity (or lack thereof) influences our perception of relative tempo in music.

## A neurocomputational model of beat-based temporal processing

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Beat processing is a fundamental aspect of music cognition involving precise, periodic temporal predictions. When presented with a beat-based stimulus, humans can quickly entrain their movements to the beat and maintain this entrainment in the face of complex rhythms, omitted beats, and tempo changes. The basal ganglia and motor planning regions (including supplementary motor area (SMA)), which play a critical role in movement initiation, have been shown to be involved in beat-based processing. However, it is unclear what roles they play and how they interact. Building upon the basal ganglia and motor cortical modeling literature, the authors propose a "two-timer" model of sub-second beat-based temporal processing in which two distinct circuits connect SMA with basal ganglia. In the first, SMA (possibly in conjunction with cerebellum) measures absolute time between perceived beats and transmits tempo estimates to putamen by inducing persistent activity in frontal or prefrontal cortex. In the second, tempo signals from putamen set the speed of a relative timekeeper in SMA. When this timekeeper reaches a certain point, a beat is anticipated and/or imagined, which cues a timer reset and disinhibition of motor activity (facilitating synchronized movements) via the basal ganglia's hyper-direct pathway. The first circuit is responsible for period correction and the initial stages of synchronization, while the second is responsible for phase correction and beat continuation. A tonic dopaminergic signal is modulated by the accuracy of predictions and moderates competition between the two circuits. This model reproduces certain data on phase correction (Repp et al. 2012) and period correction (Repp & Keller 2004), and provides a possible mechanism for some timing-related aspects of Parkinson's disease, including the efficacy of a metronomic pulse in alleviating freezing of gait. This "two-timer model" represents a first step in building biologically-realistic models of beat-based temporal processing, and makes several testable predictions.

# Silent singing: Investigating visual perceptual narrowing of rhythm from a developmental perspective

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In the field of rhythm perception, past research has mainly focused on auditory-perceptual-narrowing with little focus on visual-perceptual-narrowing. The purpose of this study is to determine if the visual system narrows in a similar manner to the auditory system and to determine which system is better at detecting rhythmic differences across cultural boundaries, e.g. Western vs. Non-Western rhythms. Using a within-subjects design participants watch videos of a woman signing the same or different Western and Balkan rhythms. The vocals are removed from the video, leaving just the movement of the woman's mouth. Participants watched two videos in a row that contain either Western, or Balkan rhythms and respond if the videos were the same or different. Preliminary behavioral data (N=12) demonstrates a significant difference in accuracy across Balkan (64%) versus Western (80%) visual rhythms ($t(11) = 3.00$, $p = 0.012$), showing a similar pattern to adult's auditory-perceptual-narrowing. Participant's eye movement were also tracked using an eye tracker to examine looking pattern changes across the Western and Balkan rhythms. The anticipated outcomes are that the participants will focus more on the eyes of the singer if a Western rhythm is presented, but more on the mouth if a Balkan rhythm is presented as is the case for native versus non-native languages. The eye data for the available sample will be discussed in the presentation to assess if it matches the behavioral data outcome.

## Recurrent timing nets for rhythmic expectancy

Peter Cariani

I will outline a theory of rhythm perception based on recurrent timing nets (RTNs). Timing nets are signal-centric neural networks that operate via interactions of temporally-coded signals. The simplest neural representation of rhythm is direct temporal coding, i.e. temporal patterns of spikes associated with event onsets, and the simplest form of temporal pattern memory is a delay line.

RTNs consist of arrays of delay loops single- or multi-synaptic delay paths) with different recurrence times and adaptive, facilitating/depressing coincidence detectors that compare the delayed signal event patterns with incoming ones (Cariani, "Temporal Codes, Timing Nets, and Music Perception", JNMR, 30(2):107-135, 2001; Cariani, "Temporal memory traces as anticipatory mechanisms", Nadin, ed. Anticipation in Medicine, pp. 105-136, Springer. 2017).

Each delay loop functions roughly as an adaptive comb filter whose loop gain increases when the delayed and current signals are highly correlated and decreases when these are only weakly so. Because incoming temporal patterns propagate through the delay loops to present the pattern again at their characteristic delay, these delay networks can function as complex, self-organizing pattern-oscillators. The representation of the rhythmic pattern expectancy is the sum of all of the arriving adaptively-weighted recurring signals at any moment. The processing resembles an adaptive (nonlinear) running-autocorrelation/comb filter signal processing and analysis.

Such RTNs may potentially account for rhythmic pattern induction (buildup of a groove, the expectation of an exact repetition of a pattern of events) and metrical pattern induction (a regular temporal expectancy "frame" of accented/unaccented events irrespective of exact repetition). The nets build up temporal pattern expectancies to the extent that the event patterns are correlated with themselves, and adaptively adjust to the duration of repeated event sequences. When patterns regularly repeat, the pattern builds up in delay loop(s) whose recurrence times equal the (fundamental) period of the pattern and its multiples. When there are no repeated event patterns, expectancies revert to individual event probabilities.

A complex, latency-based pulse pattern code is proposed that incorporates onset timings and event attributes (accent, pitch, timbre, loudness, duration), such that RTNs can chunk/separate events on the basis of common patterns of these features.

Key questions involve similarities and differences of RTNs, autocorrelation analysis, and other kinds of oscillatory networks. Can such networks be realized using multisynaptic delay paths (synfire loops)? How do we account for perception of rhythmic pattern invariance despite changes in tempo?

## New developments in neural resonance theory

Ed Large

Music Dynamics Lab, University of Connecticut

Dynamic Attending Theory (DAT) and Neural Resonance Theory (NRT) attempt to explain how humans coordinate attention, perception, and action with complex, time varying signals. In this talk I discuss how these two distinct theoretical frameworks are related, arguing that DAT is a specific model of attention that can be subsumed under the more general NRT framework. I review recent advances in NRT and discuss how these relate to dynamic attending. In so doing, I address specific criticisms of DAT and NRT that have recently arisen in the literature. I conclude by arguing that principles of dynamical systems can be leveraged to provide a powerful, explanatory framework for studying the dynamic nature of perception, action, and cognition.

# Rhythmic facilitation of temporal prediction: testing the neural entrainment hypothesis

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Every human culture has some form of music with a beat: a regularly-occurring perceived pulse in an auditory pattern to which people can synchronize or entrain when dancing. Beat perception is a predictive process which involves complex mechanisms that are not well understood and seems to involve the motor system (even when not moving). Beat-based processing also has interesting connections to many disorders involving timing disruptions, ranging from Parkinson's disease to dyslexia. To investigate the neural mechanisms of beat perception at the circuit level, we need a model species. The zebra finch (*Taeniopygia guttata*) is a promising candidate with excellent auditory discrimination, well-studied auditory abilities, and strong auditory-motor connections (due to vocal learning). Our first step in evaluating the suitability of the zebra finch as a model system for studying beat perception is to identify whether these birds can discriminate regular versus irregular sequences of sounds. To address this question, we have developed an automated operant conditioning system to test rhythm perception in this species. Preliminary data show that zebra finches (n=6) can successfully use the apparatus to discriminate between rhythmic and arrhythmic sequences at several tempi and can generalize this discrimination to novel tempi within the trained range. We plan to test whether the birds can generalize this discrimination to tempi outside of this range, which would more conclusively demonstrate the ability to form categories for rhythmic vs. arrhythmic sound patterns. We also plan to investigate the role of the auditory-motor connections in rhythm perception and temporal prediction via direct manipulation of motor areas necessary for song production. Developing an animal model of rhythm perception would open the door to more fine-grained studies, including the role of specific neural pathways and mechanisms, and lead to a more complete understanding of the mechanisms underlying human rhythmic abilities.

## Developing an avian model for human rhythm perception

Rouse, A.A., Patel, A. D., & Kao, M.H.

Every human culture has some form of music with a beat: a regularly-occurring perceived pulse in an auditory pattern to which people can synchronize or entrain when dancing. Beat perception is a predictive process which involves complex mechanisms that are not well understood and seems to involve the motor system (even when not moving). Beat-based processing also has interesting connections to many disorders involving timing disruptions, ranging from Parkinson's disease to dyslexia. To investigate the neural mechanisms of beat perception at the circuit level, we need a model species. The zebra finch (*Taeniopygia guttata*) is a promising candidate with excellent auditory discrimination, well-studied auditory abilities, and strong auditory-motor connections (due to vocal learning). Our first step in evaluating the suitability of the zebra finch as a model system for studying beat perception is to identify whether these birds can discriminate regular versus irregular sequences of sounds. To address this question, we have developed an automated operant conditioning system to test rhythm perception in this species. Preliminary data show that zebra finches (n=6) can successfully use the apparatus to discriminate between rhythmic and arrhythmic sequences at several tempi and can generalize this discrimination to novel tempi within the trained range. We plan to test whether the birds can generalize this discrimination to tempi outside of this range, which would more conclusively demonstrate the ability to form categories for rhythmic vs. arrhythmic sound patterns. We also plan to investigate the role of the auditory-motor connections in rhythm perception and temporal prediction via direct manipulation of motor areas necessary for song production. Developing an animal model of rhythm perception would open the door to more fine-grained studies, including the role of specific neural pathways and mechanisms, and lead to a more complete understanding of the mechanisms underlying human rhythmic abilities.

## Is noise only nuisance? Adding extrinsic noise enhances timing accuracy

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Mastering a motor skill is characterized by a decrease in variability, typically interpreted as a reduced level of noise corrupting the accurate control and coordination of movements. However, consistent with advances in the physical sciences, there is an increasing realization that noise may also have beneficial effects, such as stabilizing, destabilizing or masking undesired properties of a complex nonlinear system (Sternad, 2018). This study will examine whether adding noise to the feedback of motor performance can have positive effects, such as sharpening intrinsic control processes or channeling the intrinsic noise into task-irrelevant dimensions.

The model task for this experimental investigation is a virtual throwing task, where subjects aim to accurately hit a target. Previous studies in our lab identified that successful throws are achieved with a timing accuracy of 15 ms, even though redundancy in the task afforded a manifold of solutions affording an extended window for the timing of ball release. This study examined whether adding extrinsic noise to the timing of ball release could exert 'pressure' on subjects' timing precision, leading to more accurate target hits through exploiting of the timing window or better timed ball releases.

Two groups of 10 subjects practiced a throwing task inspired by the British pub game skittles for 11 daily sessions. From day 3 to 8, one group received noise added to the time of ball release: at each throw, the veridical angle and velocity of the ball release was modified by noise resulting in an altered ball trajectory. The control group received feedback with veridical measures. Error was defined as the minimum distance between the ball trajectory and the target. Mathematical analyses of the task model show that the task had redundancy as an infinite number of angle-velocity combinations can successfully hit the target, defining a solution manifold. Two metrics were calculated based on the hand trajectory in the solution space. Timing error quantified the difference between actual ball release time and the release time that would have achieved the minimum error. Timing window quantified how long the hand trajectory aligned with the solution manifold. We hypothesized that the added noise would further decrease timing error and increase the timing window compared to the control group.

Results showed that subjects in the noise group indeed performed significantly better than the control group. This hitting success was due to a decrease in timing error. Counter to expectation, the timing window did not increase. Importantly, this improvement in timing error persisted on days 9 to 11 after the noise was withdrawn. These findings demonstrate that humans can reduce their intrinsic noise in timing when faced with enhanced extrinsic noise. Importantly, this strategy persisted even without extrinsic noise, indicating beneficial effects of variability in sensorimotor learning.

Sternad, D. (2018). It's not (only) the mean that matters: variability, noise and exploration in skill acquisition. *Current Opinion in Behavioral Sciences, 20*, 183-195.

# Improved motor timing enhances time perception

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Previous studies demonstrated that motor timing and time perception share common mechanisms and brain processes. For instance, participants who displayed larger timing variability in single-finger rhythmic tapping also demonstrated lower acuity in time perception (Keele et al., 1985; Schubotz et al., 2000). However, these studies examined simple movements, i.e. finger or foot tapping, performed in an explicitly rhythmic fashion. It is unclear whether the inherent timing of more complex movements without explicit periodicity also affected time perception. Here, we examined whether practicing a sequence of controlled throwing movements enhances the sensitivity of time-interval discrimination and, if so, whether this enhanced sensitivity is selectively linked to the timing of the trained movement.

In the experiment, participants (n=14) practiced throwing a ball to hit a target in a virtual environment over 4 days. Following each throwing session, they also performed a time-interval discrimination task. After 4 days of throwing practice, participants stabilized the movement time between the onset of the throwing movements and the ball release to approximately 300 ms. In the perceptual discrimination task, participants reported which of the first standard (300, 600, 1000, or 3000 ms) or the second comparison time-interval both marked by two auditory beeps was longer. With throwing practice, they enhanced the sensitivity of time discrimination selectively for the interval of 300 ms, but not for others. These results demonstrated that improvement of motor timing enhances the sensitivity of time perception, even for timing patterns inherent to a more complex motor task. We interpret these finding that there is a shared temporal mechanism between perception and movement regardless of rhythmicity or complexity of the motor tasks.