Beat perception in the “swarm”: a look at tapping synchronization strategies using coupled metronomes

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Introduction

Negotiating Tempo in a Musical Ensemble

- **Beat Entrainment/Induction** – perception of a regular isochronous pulse that arises in the presence of musical stimuli that is fundamental to musical cognition [1].
- Developing an **internalized sense of beat** is fundamental to musical ensemble performance [2].
- **Sound-onsets as cues**– performers will resolve differences in amplitude or spectral sound-onset timings from individual players to synchronize to a beat.

Coupled Oscillator Networks to Simulate a Loosely-synchronized Group of Beats

- **Kuramoto Model** – basic model of phase synchronization in a group of oscillators via coupling parameters that connect oscillators to each other [3].
- **Ensemble Synchronization** has been simulated with Kunramoto model [4] as well as bidirectional-delayed coupled oscillator models [5,6].
- **Generative Rhythmic Stimuli** – clicking metronome audio sample is triggered once per cycle (at the zero crossing) for each of the N oscillators in the group.

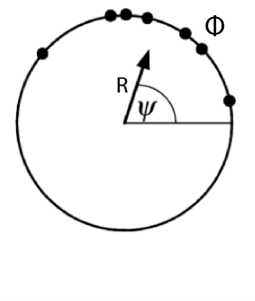
$$\dot{\phi}_i = \omega_i + \frac{K}{N}\sum^{N} sin(\phi_j - \phi_i - \alpha_o)$$

$$Re^{j\psi} = \frac{1}{N}\sum^{N} e^{j\psi_i}$$

$$\dot{\phi}_i = \omega_i + \Lambda_e(\phi_i) + KR\sin(\psi - \phi_i)$$

N = number of oscillators
$\dot{\phi}_i$ = instantaneous frequency of i^{th} oscillator
ω_i = initial frequency of i^{th} oscillator
K = coupling coefficient
ϕ_j = phase of j^{th} oscillator in group
ϕ_i = phase of i^{th} oscillator
$\Lambda_e(\phi)$ = external forcing term
α_o = "frustration" phase-forcing

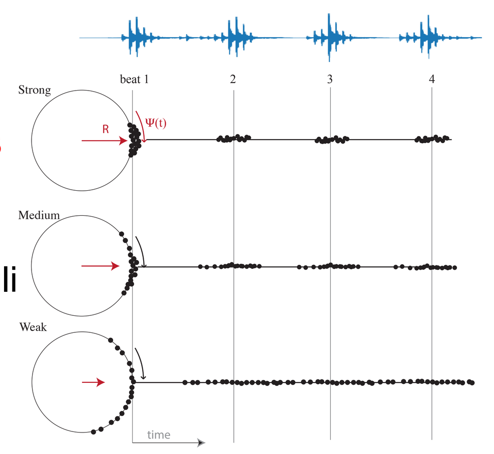
Complex Order Parameters
φ = average phase angle of group
R = phase coherence (synchrony)



Study Questions and Design

How does people’s understanding of the ‘beats’ change with the strength of the ‘coupling’ parameter between stimulus oscillators?

Are there different patterns in beat-extracting behaviours across individuals?



To examine this question, we asked people to perform finger-tapping to the stimuli where they “feel the beat.”

- Four coupling conditions (strong, medium, weak, none) for 40 “coupled metronomes” with robbing across five base tempo (e.g., an initial setup for oscillators, 72–120 bpm) were used for stimulus sequences.
- Inter-tap intervals (ITIs) and phase coherence of the tap timings over the course of the stimulus sequence are analyzed.

Methods

Participants

- 61 participants participated online (recruited from Stanford University and Amazon Mechanical Turk).
- Tap responses were filtered using our experimental criteria for tap fidelity which resulted in 41 data sets included in the final analysis.
- Participant age (years): M = 37.3, SD = 12.6.
- Music training (years): M = 4.1, SD = 6.3.

Procedure and Apparatus

- Online Study: participants requested to use headphones, mono presented to both ears.
- Subjects tapped on spacebar on their computer over the course of the stimulus sequence (~20 beats).
- Subjects were randomly assigned 1 of the 4 versions of the study, which randomized the order of blocks and conditions.

Data analysis

- Tempo-Normalized Inter-tap Intervals (nITIs: ITI divided by the base tempo beat interval) were extracted to aggragate the data across different tempo. The data for the first 18 beats were further split into temporal beat sections each consisting of 3 beats (1-3, 4-6, 7-9, 10-12, 13-15, 16-18).
- Phase coherence parameters of generative model were used to derive reference beat locations for comparison of ITIs between stimuli and participant beat placements.

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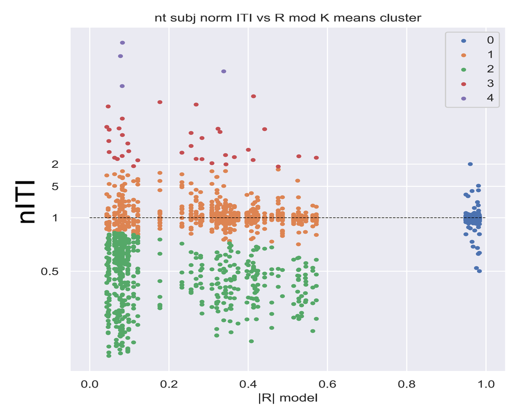
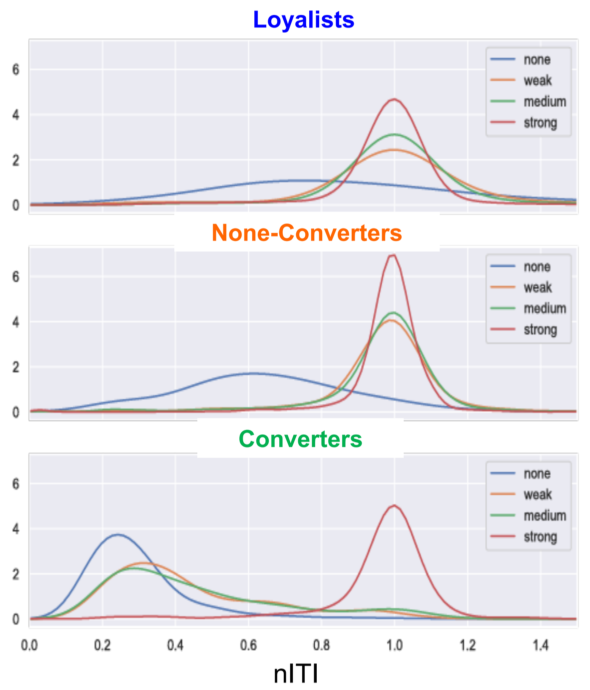
Results – Normalized Inter-Tap-Intervals (nITIs) Clustering

K-Means Clustering of all nITI data revealed 5 different behavioral patterns (as function of Stimulus phase-coherence |R|)



Distribution of nITIs in the three tap-strategy groups across four coupling conditions.



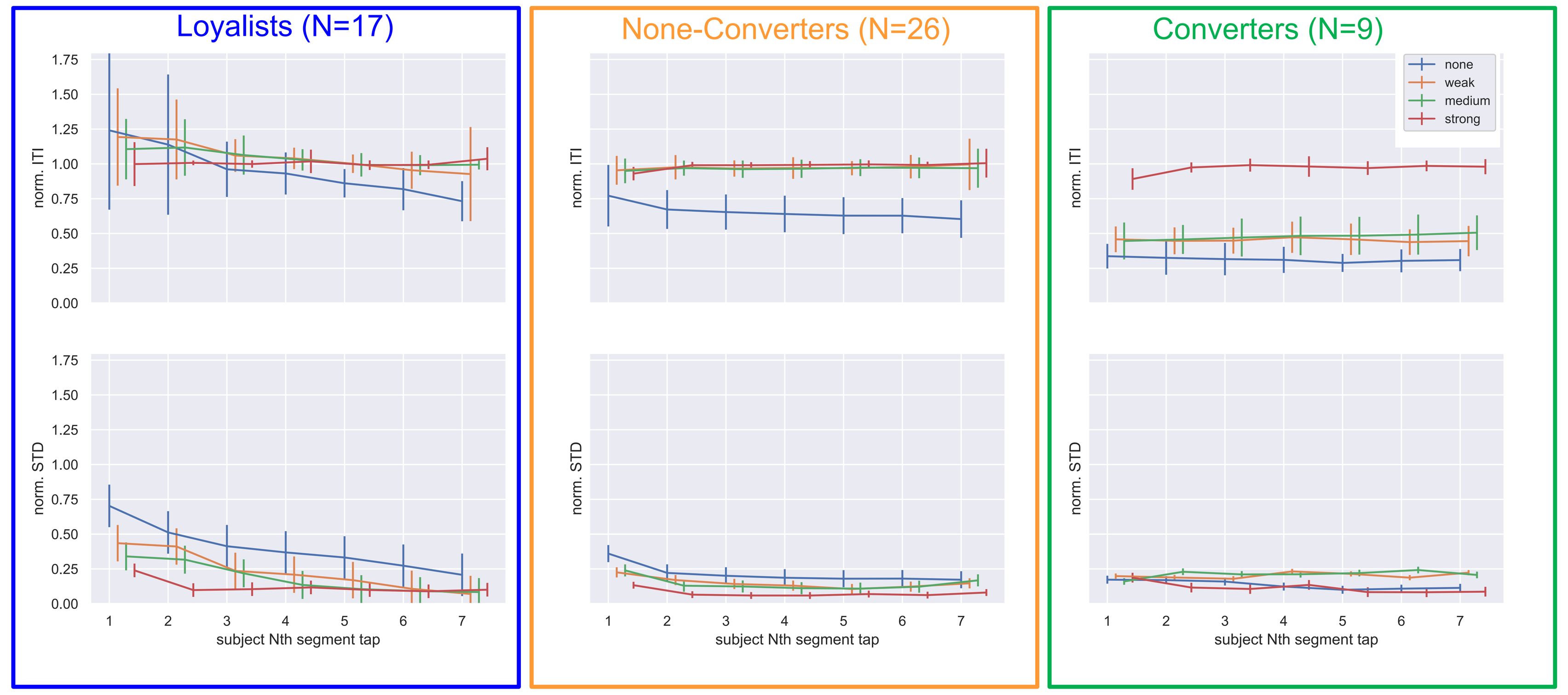
Examining these taps revealed **three groups of individuals with distinct tapping strategies:**

- ***Loyalists*** (N=17) who maintained one tap per stimulus beat.
- ***None converters*** (N=26) who did quasi double-time tapping (ITI ≈ 0.5) only for the No-coupling stimuli.
- ***Converters*** (N=9) who performed double-time tap for Medium, Weak, and No-coupling stimuli (except for Strong)

There was no significant demographic difference between 3 groups (music experience, age, gender)

Results – Time Course of nITI Change within a Trial

The mean and SD of nITIs in beat sections (3-beat windows) are examined over the course of single trial in three tapping-strategy groups.



The data show group mean. The error bar represents standard deviation across individuals.

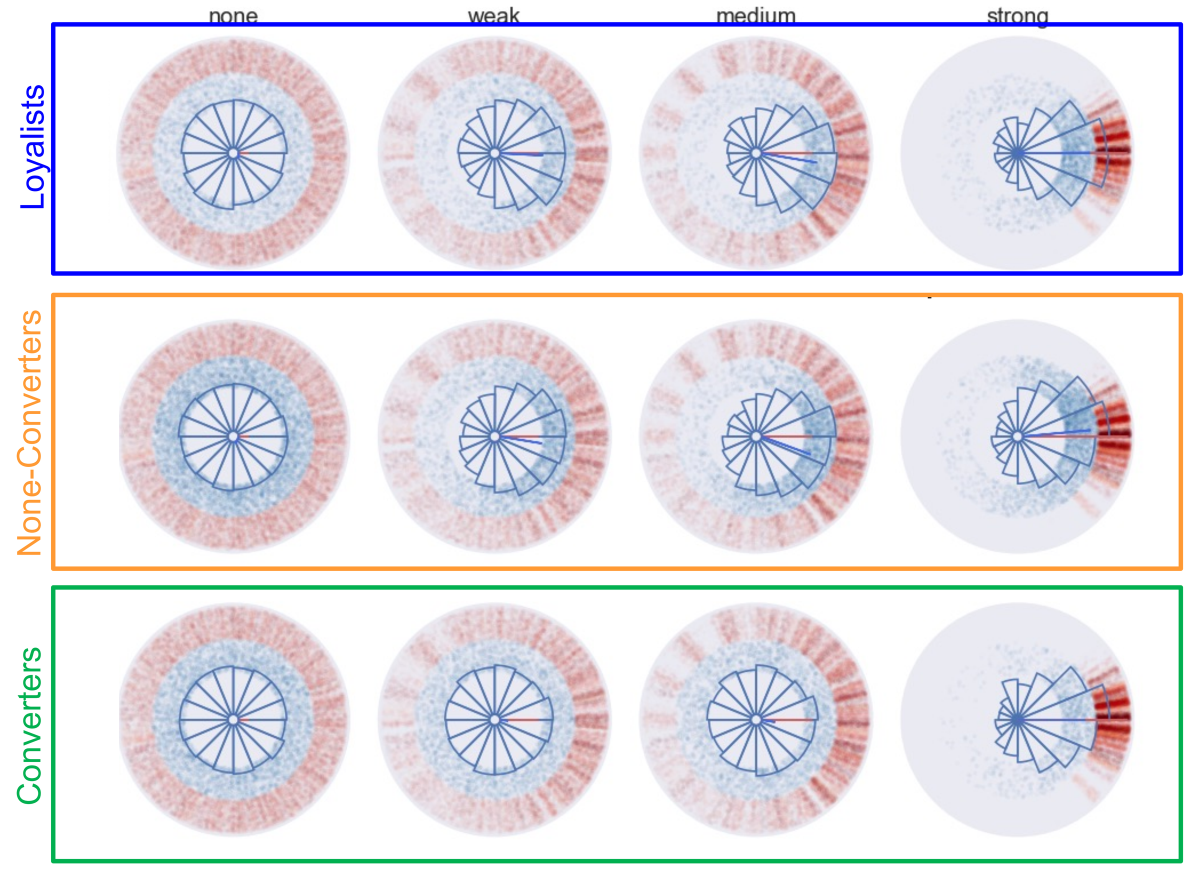
- Overall, participants synchronized better with more strongly-coupled stimuli.
- Participants adapted quickly into a steady tapping rate within the first 3 beats and tended to reduce their tap variability over time.
- All participants including loyalists tapped at a shorter interval for the none-coupled sounds.
- Loyalist and None-converter groups showed accelerations for none-coupled sounds, while Converter group show little changes over the beat sections across coupling strengths.

Conference

This poster was presented at the *Neurosciences and Music – VII Conference*: Connecting with music across the lifespan – June 18 - 21, 2021 Aarhus, Denmark.

Results – Phase Coherence

Phase Coherence of Participants (blue) vs. Stimulus Oscillators (red) were visualized below. Each coherence measure R is indicated with a phasor (vector), where its length shows the strength of the phase synchronization, and its angle shows the most agreed phase (for the stimulus, it’s always set at 0 degree)



Rayleigh uniformity tests were used to confirm the directionality of the phase coherence phasors. Watson-Wheeler test for homogeneity suggest that the distributions (subject, stimuli for each coupling cond.) come from different distributions.

For coupled stimuli, the $|R_{subjects}| < |R_{model}|$ for the strong coupling but $|R_{subjects}| > |R_{model}|$ for the medium, weak, and no coupling conditions.

Taps are generally aligned with the phase (Ψ_{model}) of the stimulus, suggesting the extraction of the center of the stimulus density even for weaker coupling conditions.
The Converters’ taps show almost uniform distribution of the taps even for the medium coupling stimuli.

Conclusions

1. **In line with the literature, participants quickly improved their tap consistency at the beginning of a trial.**
2. **Except for the strongest coupling, individuals adapt different tapping strategies to accommodate weaker coupling conditions. In particular, 2/3 of participants convert to tapping at a faster rate (2-4 beats) with none-coupling stimuli, similar to the previous findings with very short stimulus onset intervals [7].**
3. **Such increased tapping rates for weakly coupled stimuli may point to the “density-mimicking” strategy that works with a short temporal window.**
4. **Stronger phase coherence across participants than oscillators for weakly coupled stimuli suggests a commonly shared mechanism for “feeling the beats” out of the sound onset density characteristics.**

References

1. Patel, A. (2008). Beat-based rhythm processing as a key research area", In Music, Language and the Brain (pp. 402–415). Oxford: Oxford University Press.
2. Honing, H. (2012). Without it no music: Beat induction as a fundamental musical trait, Annals of the New York Academy of Sciences., 1252, 85–91. https://doi.org/10.1111/j.1749-6632.2011.06402.x
3. Kuramoto, Y. (1975). Self-entrainment of a population of cou- pled non-linear oscillators, *International Symposium on Mathematical Problems in Theoretical Physics, Lecture notes in Physics*, vol. 39, no. H, pp. 420–422.
4. Heggli, O. A., Cabral, J., Konvalinka, I., Vuust, P. & Kringelbach, M. L. (2019). A Kuramoto model of self-otherintegration across interpersonal synchronization strategies. *PLoS computational biology, 15*(10), e1007422. https://doi.org/10.1371/journal.pcbi.1007422
5. Roman, I. R., Washburn, A., Large, E. W. , Chafe, C., & Fujioka, T. (2019) .Delayed feedback embedded in perception-action coordination cycles results in anticipation behavior during synchronized rhythmic action: A dynamical systems approach, *PLoS computational biology, 15*(10), e1007371. https://doi.org/10.1371/journal.pcbi.1007371
6. Demos, A. P., Layeghi, H., Wanderley, M. M., & Palmer, C. (2019). Staying Together: A Bidirectional Delay-Coupled Approach to Joint Action. Cognitive science, 43(8), e12766. https://doi.org/10.1111/cogs.12766
7. Elliott, M. T., Wing, A. M., & Welchman, A. E. (2014). Moving in time: Bayesian causal inference explains movement coordination to auditory beats. *Proceedings. Biological sciences*, 281(1786), 20140751. https://doi.org/10.1098/rspb.2014.0751