Perceiving temporal regularity in music

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Introduction

- People have effortless ability to perceive temporal regularity in musical sequences.
- Listeners perceive temporal fluctuations or deviations as related to performers’ musical intentions. (duration-lengthening)
Introduction

The approach in this paper:

1. Model

- Internal Oscillations
- External Driving Signal

Beat perception Note Events

Introduction

The approach in this paper:

2. Experiments

- a. Evaluate the model’s ability to track different temporal periodicities
- b. Test the model’s ability to detect temporal irregularities
Some basic concepts

- **Rhythm**: the general sense of movement in time, including phrasing, harmony and meter.
  - *Temporal patterning of event durations in a sequence*

- **Beat**: pulses marking equally spaced points in time
  - *Once it is established, it may continue in mind*

- **Metrical Structure**: alternation of strong and weak beats over time

Strong beats and weak beats

- Strong beats: points at which many beats are coincide
- Weak beats: points at which few beats are coincide
- The first position in the measure is a strong beat
- Inter-onset intervals (IOIs)
*Meter perception model (Sketch)*

**Model of single oscillator (prerequisite)**

- **Oscillations** are period events ($T_0$)
- **Phase** at any time $t$: $\phi = \frac{t}{T_0}$ (between 0 and 1)
- **Synchronized**: two oscillations regularly come into phase or begin their cycles together.
- **Entrainment**: a process by which two or more oscillators achieve synchronization
- Entrainment occurs because a **coupling** between two or more oscillations causes them to synchronize
- **Coupling** allows one oscillator to perturb another by altering its **phase**, its **intrinsic period**, or both

*Meter perception model (Sketch)*
Model of single oscillator (prerequisite)

\[ \phi_{n+1} = \phi_n + \frac{t_{n+1} - t_n}{p} \]

- Phase of driving oscillator at which the driven oscillator fires on iteration \( i \)
- \( p \) is the period of driven oscillator
- \( \Phi > 0 \), event occurred late;
- \( \Phi = 0 \); corresponds to time of the expected beat;
- \( \Phi < 0 \); event occurred early;

Model of single oscillator

\[ \phi_{n+1} = \phi_n + \frac{t_{n+1} - t_n}{p} - \eta \cdot X_n \cdot F(\phi_n, k) \quad (mod -0.5, 0.5) \]

- \( F(\Phi, k) \) is the non-linear coupling function;
- \( X_n \) is the amplitude of the nth onset (=1)
- \( \eta \) is the coupling strength
- \( k \) is a focus or concentration parameter that determines the extent of an expectancy function
Expectancy function and Phase resetting function

\[ f(\phi, \kappa) = \frac{1}{I_0(\kappa)} \exp \kappa \cos 2\pi \phi \]

\[ F(\phi, \kappa) = \frac{1}{2\pi \exp \kappa} [\exp \kappa \cos 2\pi \phi \sin 2\pi \phi] \]

- **Period coupling:**

\[ p_{\phi n+1} = p_\phi n (1 + \eta_p X_n F(\phi_n, \kappa_n)) \]

\[ \phi_{n+1} = \phi_n + \frac{t_{n+1} - t_n}{p_n} - \eta_{\phi} X_n F(\phi_n, \kappa_n) \pmod{0,5,0,5} \]

Modeling hierarchical metrical structures (inter-coupling)

- Musical rhythms typically contain multiple periodicities
- The internal oscillators are coupled to one another so as to preserve certain phase and period relationships
- Phase coupling strength \( \alpha_{\phi} \)
- Period coupling strength \( \alpha_p \)

- Mixture of von Mises distributions

\[ f_j(\phi) = \frac{1}{I_0(\kappa_j)} \exp \kappa_j \cos 2\pi / \phi \]

\[ f(\phi, \kappa) = \sum_j w_j f_j(\phi) \]
Sensitivity to temporal fluctuations:
1. Categorizing note onsets

To find the associated level for every note event

Calculation:

\[ f_j(\phi) = \frac{1}{I_0(\kappa_j)} \exp \kappa_j \cos 2\pi\phi \]

\[ f(\phi, \kappa) = \sum_j w_j f_j(\phi) \]

\[ \tau_j = \frac{w_j f_j(\phi)}{f(\phi, \kappa)} \]

Sensitivity to temporal fluctuations:
2. Detecting Phrase-final lengthening

- \( P_{D(n)} \): Probability that the event was heard as deviating from its expected time.
- \( P_{L(n)} \): Probability that the event was heard as occurring late in the cycle.

\[ P_{D(n)} = 2 \int_{x=0}^{\phi_1} f(x, \kappa) \, dx \]

\[ P_{L(n)} = \int_{x=-0.5}^{\phi_n} f(x, \kappa) \, dx \]

\[ P_{P(n)} = P_{D(n)} P_{L(n)} \]
**Experiment (horizontal temporal fluctuations)**

- Test sets: Piano performances of 2- and 3-part inventions by Bach.
- 6 players* 4 phrase conditions *2 voice entrances *3 excerpts=144 performances
- The simulated oscillations tracked the 16th-note and 8th-note levels of the metrical structure
- Parameters: $p_{16th}=$ initial IOI=$1/2*p_{8th}$; $\Phi_0=0$; $k=3$; $\eta_\Phi =1.0, \eta_p =0.4, \eta_k =0.2$
  \[ \alpha_\Phi = \alpha_p = 1/0 \] (coupled/uncoupled)
- Analyzed by circular statistics

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**Performance timing experiment**

- Performance timing $\Phi = \frac{t_{\text{onset}} - t_{\text{expected}}}{p}$
- Dev16th>Dev8th, more expressive timing at the 16th-note level
- Events on and around the notated boundaries had larger relative phase
- Pianists significantly lengthened events at phrase boundaries
Model tracking experiment

- Phase: $\phi_{n+1} = \phi_n + \frac{t_{n+1} - t_n}{p_n} - \eta_\phi \sum F(\phi_n, \kappa_n) \mod 0.50.31$

- Angular Dev=0.0801 (smaller than Angular Dev of performance timing)

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The model adapted phase and period to track the ongoing sequences

- 1. Different phrase conditions:
  - The model tracked better in the natural phrase than in the experimental phrase conditions

- 2. Different metrical level:
  - The smaller level showed more variability

- 3. Different voices:
  - Equally well

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Model tracking experiment

4. Coupled and Uncoupled

- Tracking by coupled oscillators was better than by the uncoupled oscillators.
- The coupled oscillator model consistently outperformed the uncoupled model, and more so at the smaller metrical level (16th-note)
Experiment of detecting phrase boundaries

Table 1
Number of events passing lengthening criterion for performance and model

<table>
<thead>
<tr>
<th>Model</th>
<th>Performance</th>
<th>&gt;75%</th>
<th>&lt;75%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>234</td>
<td>120</td>
</tr>
<tr>
<td>&gt;.75</td>
<td></td>
<td>(64%)</td>
<td>(12%)</td>
</tr>
<tr>
<td>&lt;.75</td>
<td></td>
<td>121</td>
<td>935</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(36%)</td>
<td>(88%)</td>
</tr>
</tbody>
</table>

- The model probability of the event >0.75
- The IOI of the event is greater than 75% of all performed events
- Conclusion: the model was able to detect lengthening more often than chance at locations where performers used lengthening
Conclusions

- The model is good
- The first test of a multiple oscillator model tracking music performances
- The model’s beat tracking variability was slightly lower than the amount of stimulus variability
- The model detected those events that contained rubato (phrase-final lengthening) well
- The coupling of oscillators improved the model’s beat-tracking
- Coupling aided beat-tracking most at metrical levels that contained the most temporal variability.

References