Synchronization in duet performance:
Testing the two-person phase error correction model

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Overview

1. How do ensemble players manage to remain synchronized?
2. Sensorimotor synchronization, tapping along perfect metronome.
   → Synchronization is achieved by linear phase error correction.
3. Extend model to duet performance.
   → Major advantage: Use computer to simulate one of the duet partners.
4. Experimental study.
   → Preliminary data.
Definition of interresponse intervals and synchronization errors

**task:** tap in close synchrony with the metronome

**synchronization errors ("asynchronies")**

metronome

overt responses

**interresponse intervals**
The phase-correction model

(Vorberg & Wing, 1994, 1996; Vorberg & Schulze, 2002; Schulze & Vorberg, 2003)
The two-level timing model augmented by phase error correction

1. basic assumption:
   \[ T_n^* = T_n + (1 - \alpha)A_n \]

1. testable consequence:
   \[ A_{n+1} = (1 - \alpha)A_n + (T_n + M_{n+1} - M_n) - C_n \]
Model predictions I: response to experimental perturbations
Results (Antje Fuchs, 2003)
Results (Antje Fuchs, 2003)
Model predictions II:
serial or auto-covariance function (acvf)

serial variance = acvf at lag 0 = acvf(0)

$A_1 \ A_2 \ A_3 \ \ldots \ A_{i-1} \ A_i \ A_{i+1} \ \ldots \ \ldots \ A_{n-1} \ A_n$
Auto-covariance function (acvf)

lag 1 auto-covariance = acvf(1)
Auto-covariance function (acvf)

lag 2 auto-covariance = acvf(2)

auto-correlation function $acf(lag) = \frac{acvf(lag)}{acvf(0)}$
Predicted asynchrony acf (as a function of lag)

$0 < \alpha < 1$

$1 < \alpha < 2$

Note:
Synchronization performance is *unstable* if $\alpha$ outside this range.
Basic assumption: Each player serves as metronome for the other one.

Parameters:
Player A (subject)
- timekeeper variance \( \sigma_T^2 \)
- motor variance \( \sigma_M^2 \)
- error correction \( \alpha \)

Player B (metronome)
- timekeeper variance \( \sigma_U^2 \)
- motor variance \( \sigma_N^2 \)
- error correction \( \beta \)
Two-person phase synchronization model: Main result

**Predicted 2-person asynchrony acvf**

\[
\text{var}(A) = \\
\left[ (\sigma_T^2 + \sigma_U^2) + 2(\alpha + \beta)(\sigma_M^2 + \sigma_N^2) \right] \\
/ \left[ 1 - (1 - (\alpha + \beta))^2 \right]
\]

\[
\text{cov}(A_n, A_{n+k}) = \\
\left[ 1 - (\alpha + \beta) \right]^{k-1} \left[ \text{var}(A) \left( 1 - (\alpha + \beta) \right) - (\sigma_M^2 + \sigma_N^2) \right]
\]

**Predicted 1-person asynchrony acvf**

\[
\text{var}(A) = \\
\left[ (\sigma_T^2) + 2(\alpha)(\sigma_M^2) \right] \\
/ \left[ 1 - (1 - (\alpha))^2 \right]
\]

\[
\text{cov}(A_n, A_{n+k}) = \\
\left[ 1 - (\alpha) \right]^{k-1} \left[ \text{var}(A) \left( 1 - (\alpha) \right) - (\sigma_M^2) \right]
\]
Predicted asynchrony acf for two-person model:

1. Synchronization performance is unstable if $\alpha + \beta$ outside this range.
2. Predictions:
   - Stable but oscillatory acf for $\beta$ positive.
   - Unstable synchronization for $\beta$ negative.
Experiment: Conditions

1. tempo
   - IOI=450 ms / 300 ms

2. meter
   - duple / triple / quadruple

3. metronome gain factor
   - $\beta=0$
   - $\beta=.4 / .8$
   - $\beta=-.25 / -.50$

4. seven subjects
   - 6 one hour sessions
   - 18 sequences/condition
Results

1. Exemplary time series after six hours of practice
   - asynchronies
   - interresponse intervals, IRI (subject)
   - interonset intervals, IOI (metronome)
2. Auto-correlation functions, acf
subject an: asynchronies
(x-axis: tap no. 1 – 48; y-axis: tap-metronome asynchrony in ms)

$\beta = 0$  $\beta = 0.4$  $\beta = 0.8$  $\beta = 0.25$  $\beta = 0.50$

slow

fast

50 ms
subject an: IRIs (top) and IOIs (bottom)  
(x-axis: tap no. 1 – 48; y-axis: deviation from nominal IOI, in ms)

\[ \beta = 0, \beta = 0.4, \beta = 0.8, \beta = -0.25, \beta = -0.50 \]
subject an: acf.s for slow (top) and fast tempi (bottom)  
(x-axis: lag 0 to 6; y-axis: correlation size)

<table>
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<th>( \beta )</th>
<th>duple</th>
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<td>0</td>
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</table>
subject bv: asynchronies slow (top) and fast (bottom)

$\beta = 0$ $\beta = 0.4$ $\beta = 0.6$ $\beta = 0.25$ $\beta = 0.50$
subject bv: IRIs (top) and IOIs (bottom)

\[ \beta = 0 \quad \beta = .4 \quad \beta = .8 \quad \beta = -.25 \quad \beta = -.50 \]
subject bv: acf.s for slow (top) and fast (bottom) tempi

β = 0  β = 0.4  β = 0.8  β = -0.25  β = -0.50

duple  triple  quadruple
subject eh: asynchronies, slow (top) and fast (bottom)

\[ \beta = 0 \quad \beta = 0.4 \quad \beta = 0.8 \quad \beta = -0.25 \quad \beta = -0.50 \]
subject eh: IRIs (top) and IOIs (bottom)

\[ \beta = 0 \quad \beta = .4 \quad \beta = .8 \quad \beta = -.25 \quad \beta = -.50 \]
subject eh: acfs for slow (top) and fast (bottom) tempi

\[ \beta = 0 \quad \beta = 0.4 \quad \beta = 0.8 \quad \beta = -0.25 \quad \beta = -0.50 \]

duple triple quadruple
Empirical asynchrony acf.s (all subjects)

\( \beta = 0 \), \( \beta = 0.4 \), \( \beta = 0.8 \), \( \beta = -0.25 \), \( \beta = -0.50 \)

duple
triple
quadruple
Empirical asynchrony acvf.s (average across subjects)
(x-axis: lag 0 to 6; y-axis: autocovariance at lag k)

β = 0

β = 0.4

β = 0.8

β = -0.25

β = -0.50

duple
triple
quadruple
Summary and conclusions

1. Two-person model is in qualitative agreement with observations.
   → As predicted, $acf$ becomes oscillatory as metronome gain $\beta$ increases.
   → For negative gain $\beta$, performance is unstable for most subjects.
2. Subjects can to adapt their phase-correction strategy to that of the duet partner.
3. **Next step: Quantitative model fit.**
4. Model-based experimental paradigm is a promising tool for studying duet synchronization. The model is easily extended to musically more challenging conditions.