Timing in speech production

- How is timing among speech production events regulated to provide:
  - stability
  - flexibility

- Coupled Oscillator planning model:
  - one solution to this problem
  - leads to a dynamical representation of syllable structure
  - captures macroscopic and microscopic properties of syllable structure
Inter-gestural Timing

- Relative timing of gestures carries information.
- How is appropriate relative timing maintained?
- What is the glue?
Chain?

- Trigger gesture $i$ at given state $(x, \dot{x})$ of some other gesture $j$.

- But when two of the same gestures appear in sequence, the triggering state will be achieved too early.

- And there will be interval of time during which there will be no change in state.
Planning intergestural timing
(Saltzman, Nam, Goldstein)

- Each gesture is associated with a planning oscillator, or clock, responsible for triggering that gesture’s activation.

- Relative phase of oscillators (and therefore time of triggering) is controlled by coupling the clocks to one another.
Dynamical Systems and Coupling
Population Growth: Point Attractors

- State space: size of population
- Rule for change:
  \[ P_{n+1} = P_n + bP_n - dP_n \]
  \[ r = b - d \]
  \[ P_{n+1} = P_n + rP_n \]
- \( r \) is a control parameter of the system
- Qualitatively different system behaviors as a function of \( r \)
  - for \( r < 0 \), all initial conditions result in a final state of \( P = 0 \): point attractor in the state space.
  - for \( r > 0 \), exponential growth: no attractor

- For \( r = -0.2 \) with \( P_1 = 10 \), population size decreases over time.
- For \( r = 0.2 \) with \( P_1 = 10 \), population size increases over time.
Logistic Growth: Stable population attractors

- more realistic growth model: growth rate modulated by a gain factor that depends on the size of population that can be supported, $K$.

- $K$ is an point attractor of the system.

$$P_{n+1} = P_n + rP_n\left(\frac{K - P_n}{K}\right)$$
Coupling Predator and Prey: Periodic attractors

- The interaction of two dynamical systems can be modeled by adding a coupling term to each system, whose value depends on the states of both systems.
- Rabbits: logistic growth
- Foxes: exponential decay

\[
R_{n+1} = R_n + rR_n\left(\frac{K - R_n}{K}\right) - \beta R_n F_n
\]

\[
F_{n+1} = F_n + rF_n + 3\beta R_n F_n
\]

- For certain values of the coupling control parameter (\(\beta\)), a stable pattern of oscillation emerges: periodic attractor.
- Oscillation results from combination of mutual excitation + inhibition.

\(\beta = 0\)

\(\beta = 0.0455\)

Foxes

\(r = -0.2\)

Rabbits

\(r = 0.2\)

\(K = 10\)
Coupled oscillatory dynamical systems

• Coupled oscillators exhibit **entrainment**: They synchronize with one another

  ![Demo: Bahraminasab](image)

• Entrainment applies to living systems, including humans

• Entrainment of oscillators within an individual or across individuals

• Coupling doesn’t have to be mechanical.

• It can be informational (Saltzman, 1995).
Speech entrainment across talkers

• Development of technique for measuring articulator kinematics from two talkers simultaneously.

  • One Carstens EMA, one ND WAVE
  • Preliminary proof of concept
  • Talkers (1 M, 1 F) sat 2 m apart facing one another
    • M: “cop top cop top...”
    • F: “top cop top cop...”

Vatikiotis-Bateson, Tiede, C. Best, Kroos, Bundgaard-Nielsen
Modes of synchronization

• Systems of coupled oscillators exhibit distinct modes of synchronization (attractor states):
  • frequency-locking
  • phase-locking
  • amplitude-locking

• The relative stability of those modes can be influenced by the value of the system’s control parameters. As the values change, the state of the system can shift into a different mode.

• These modes have been shown to underlie the coordination of movements of multiple limbs in human action. (e.g., Turvey, 1990; Kelso, 1995).

• Use different modes to couple speech gesture clocks: model of syllable structure.
Synchronization modes for limb coordination: phase-locking

- Two relative phase modes (or attractors) are spontaneously available (require no learning) - Haken, Kelso & Bunz, 1985
  - 0° (in phase) most stable
  - 180° (anti-phase)
- Spontaneous transitions to most stable mode (0°) as frequency increases.
- Fluctuations in phase during transition interval.

Turvey, 1990
Visualizing Attractor Modes: Potential Functions
First-order dynamical system: Single attractor

\[ \frac{dx}{dt} = -k(x - x_0) \]

\[ x_0 = -1 \quad k = 2 \]
Potential Functions

- Dynamical systems of this type can be visualized by plotting its potential function $V(x)$.

$$V(x) = \frac{k(x - x_0)^2}{2}$$

- The change of $x$ is equal to the negative slope of the potential function.

$$\frac{dx}{dt} = -\frac{d(V(x))}{dx}$$

$$\frac{dx}{dt} = -k(x - x_0)$$
Stochastic Systems

- Noise term can be added to differential equation, which results in a distribution of final values of $x$ when differential equation is simulated multiple times.

$$V(x) = \frac{(k-x_0)^2}{2}$$ for $k=-2$; $x_0=-1$ and $k=-2$; $x_0=1$
Phase-locking Model:  
Haken-Kelso-Bunz (HKB), 1985

- **Potential** function has been proposed that can model the results of many experiments on bi-manual coordination:
  - \( V(\Phi) = -a \cos(\Phi) - b \cos(2\Phi) \)
  - two local attractors \((0^\circ, 180^\circ)\)
  - in-phase attractor:
    - **wider** (more accessible)
    - **deeper** (more stable)
  - As \(b/a\) decreases, anti-phase minimum disappears
  - Let \(b/a\) be a function of oscillation frequency.
Multiple attractors for phase-locking: 0, +/- π

\[ V(x) = -a \cos(x) - b \cos(2x) \]

\[ \frac{dx}{dt} = -\frac{d(V(x))}{dx} \]

\[ \frac{dV(x)}{dx} = a \sin(x) + 2b \sin(2x) \]

\[ \frac{dx}{dt} = -a \sin(x) - 2b \sin(2x) \]
Modes & Syllable Structure

- If planning oscillators that trigger a consonant (C) gesture and a vowel (V) constriction gesture are to be coupled in a spontaneously accessible mode (without learning), there are just two possibilities:
  - in-phase
    - hypothesized for C-V (onset relation) simplest, most stable
  - anti-phase
    - hypothesized for V-C (coda relation)
Evidence for C-V and V-C modes

Onset C and V gestures begin synchronously (Löfqvist & Gracco, 1999); Hypothesize that clocks are in-phase.

Coda C begins later than V; hypothesize that clocks are anti-phase.
Gestural Score

“two back”

Monday, November 24, 14
Gestural Score

“had made him lose”
Planning model (Saltzman, Nam, Goldstein)

- Phonological input to time planning is a **coupling graph**:
  - **NODES**: Specification of gestures and the associated planning oscillators
  - **EDGES**: coupling functions that specify preferred mode between pairs of planning oscillators.

- At the beginning of planning process, oscillators are set into motion at random phases.

- Coupling forces specific to graph cause the oscillators to settle at stabilized relative phases (Saltzman & Byrd, 2000).

- Once stabilized, timing oscillators trigger the activation of their associated gesture(s).
Example Coupling Graphs

“bad”

“mad”

“spat”
Lexicon → Coupling Graph → Gestural planning oscillator variables → Activation variables (Gestual Score) → PLANNING Inter-gestural coordination

Output speech

“bad”
LIP (lab clo) → TT (alv clo) → TB (phar wide)

Prosody → "bad"

Rate → "bad"

Tract/Constriction variables → Model articulator variables → CONSTRUCTION FORMATION Inter-articulator coordination

Nam & Saltzman (2003)
Goldstein, Byrd & Saltzman (2006)
Example: “spat”
Universality of CV structure

• The fact that in-phase is the more accessible, more stable mode contributes to an account of syllable structure typology;

• All languages have CV syllables.

• Not all languages have (C)V(C) syllables
Combinatorial Freedom

- Combination is **free** where the coupling mode is maximally accessible **without learning** (in-phase).

- Combinations are most **restricted** where learning is required.

<table>
<thead>
<tr>
<th></th>
<th>Freedom</th>
<th>Accessibility</th>
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</thead>
<tbody>
<tr>
<td>CV onset-rime</td>
<td>in-phase</td>
<td>synchrony</td>
</tr>
<tr>
<td>VC nucleus-coda</td>
<td>anti-phase</td>
<td>sequence</td>
</tr>
<tr>
<td>CC within onset, coda</td>
<td>eccentric</td>
<td>partial overlap</td>
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