Timing and coordination

Gregor Schöner

so far…

- … we have studied the generation of movement in vehicles…
- through a "behavioral dynamics" that is in closed loop with the environment
- as it takes (possibly time varying) constraints from the perceived environment
- and expresses these as contributions to the dynamics…
- whose attractor solutions then generate movement plans…

.. now we will look at

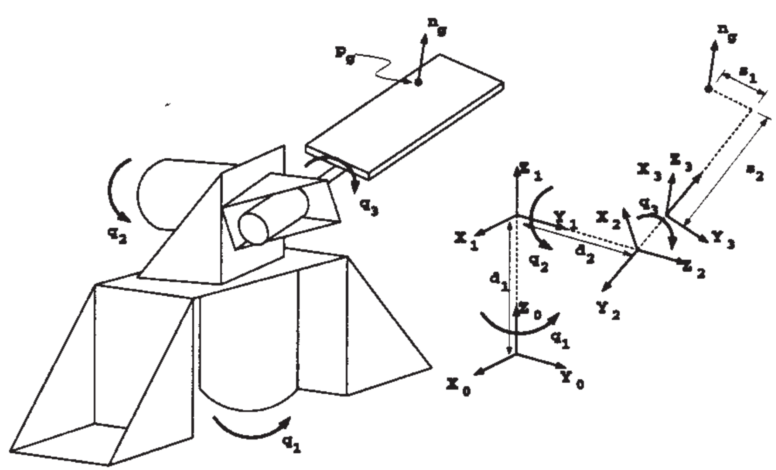
- how movements can be generated in open loop, that is, from from an internal "neural" dynamics
- this serves primarily to generate movements that are "timed", that is,
    - they arrive "on time"
    - the are coordinated across different effectors
    - the are coordinated with moving objects (e.g., catching)
- timing implies some form of anticipation…

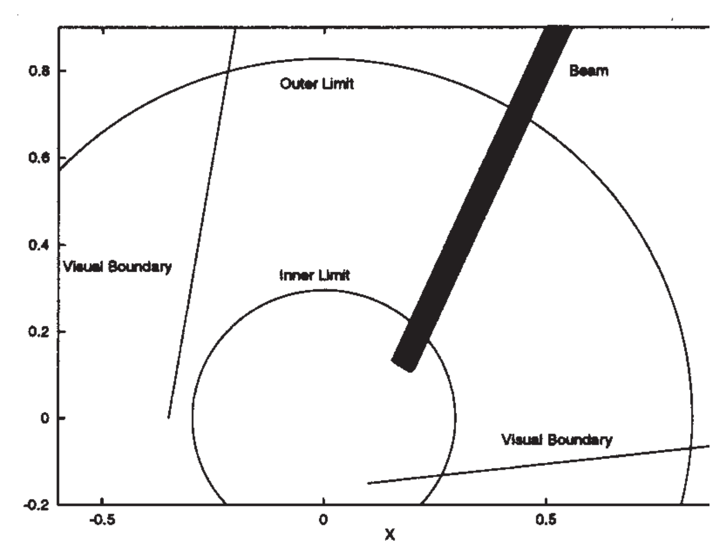
How is timing done in conventional robotics?

- classical fixed control: fixed templates of timing encoded in digital computers… determined from trajectory planning algorithms that a purely kinematic, and are realized by servo-controllers that "track" the time plan
- advanced control: the planning takes the physical dynamics into account (e.g. optimizing a cost function)

Timing in autonomous robotics

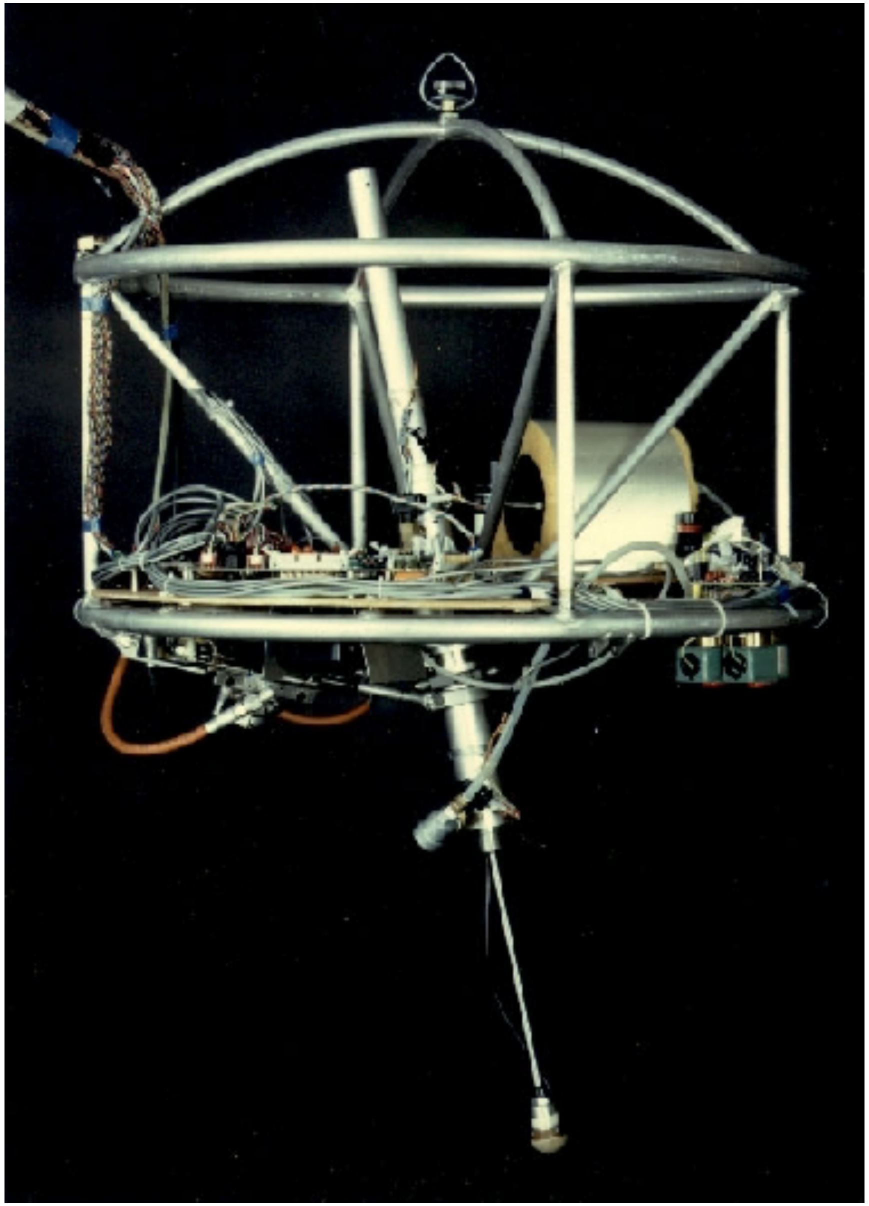
- Koditschek’s juggling robot:
  - physical dynamics of bouncing ball modeled… actuator inserts a term into that dynamics so that a periodic solution (limit cycle) results
  - ball is kept within reach by conventional P control from contact to contact





Timing in autonomous robotics

- Raibert’s hopping robots
  - dynamics bouncing robot modeled… actuator inserts a term into that dynamics so that a periodic solution (limit cycle) results
  - robot is kept upright by controlling leg angle to achieve particular horizontal position for Center of Mass

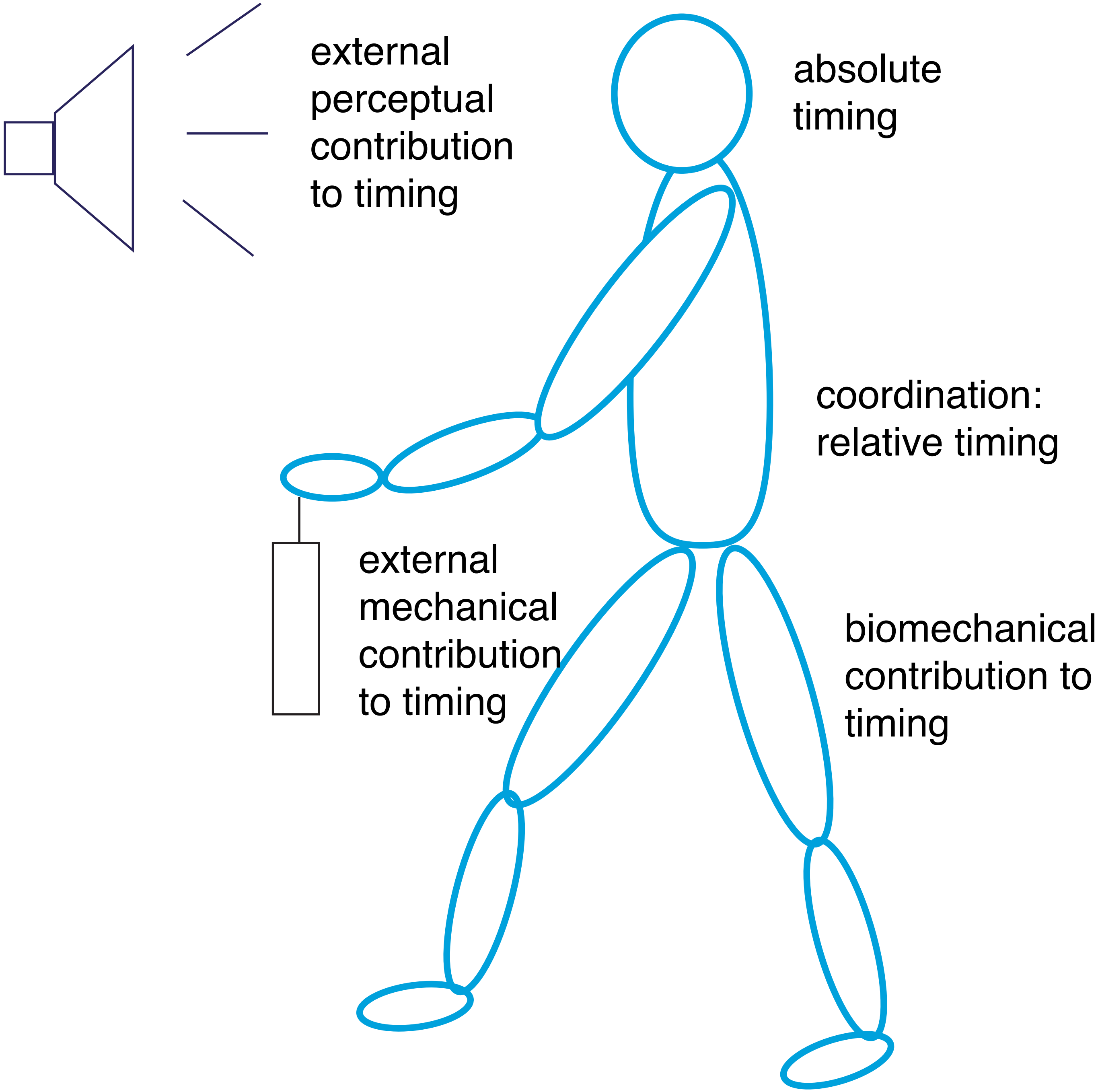


How is timing done in conventional robotics?

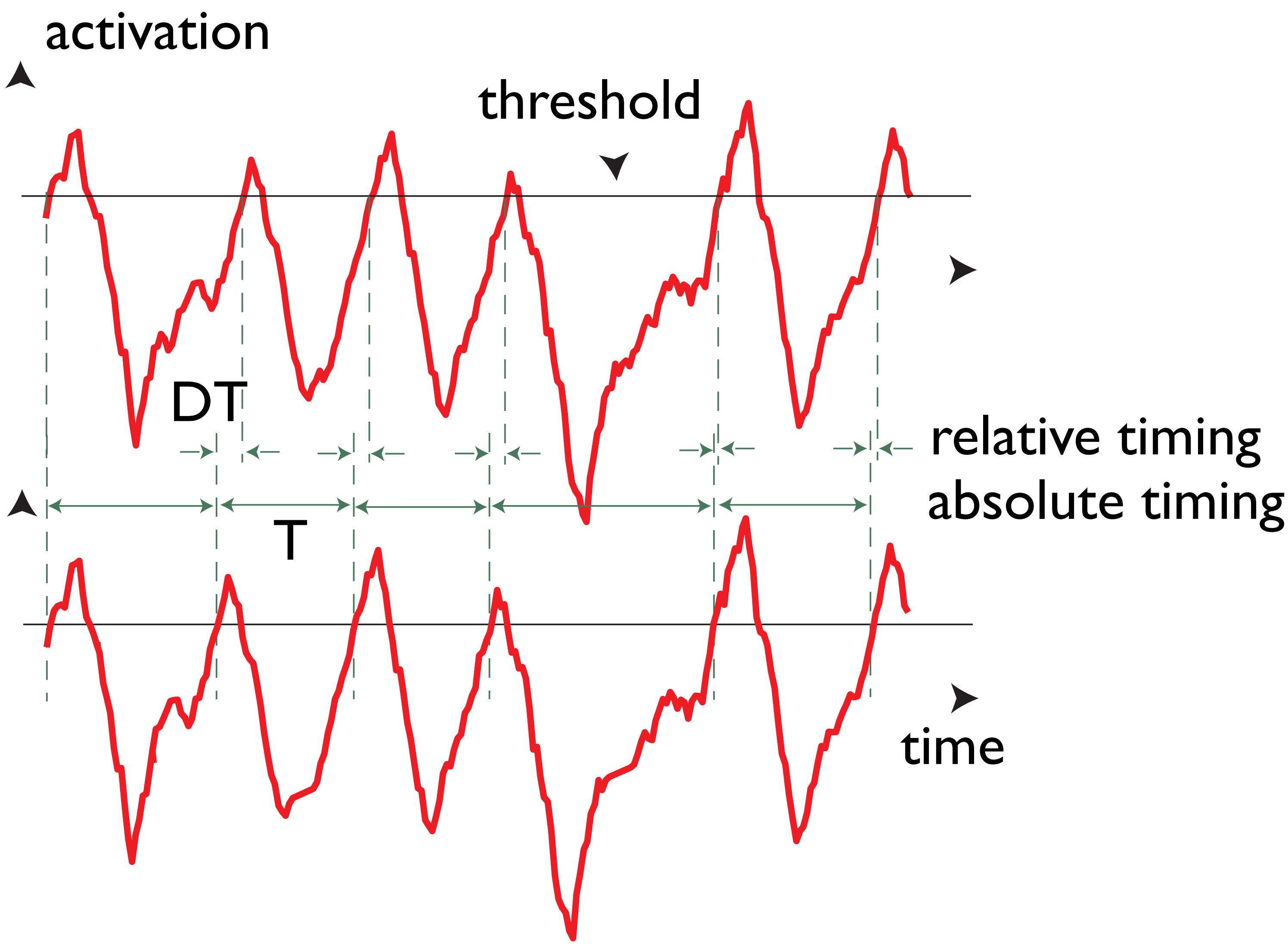
- Raibert's bio-dog
  - expand that idea by coordination among limbs

https://www.youtube.com/watch?v=M8YjvHYbZ9w

Timing in nervous systems



Relative vs. absolute timing



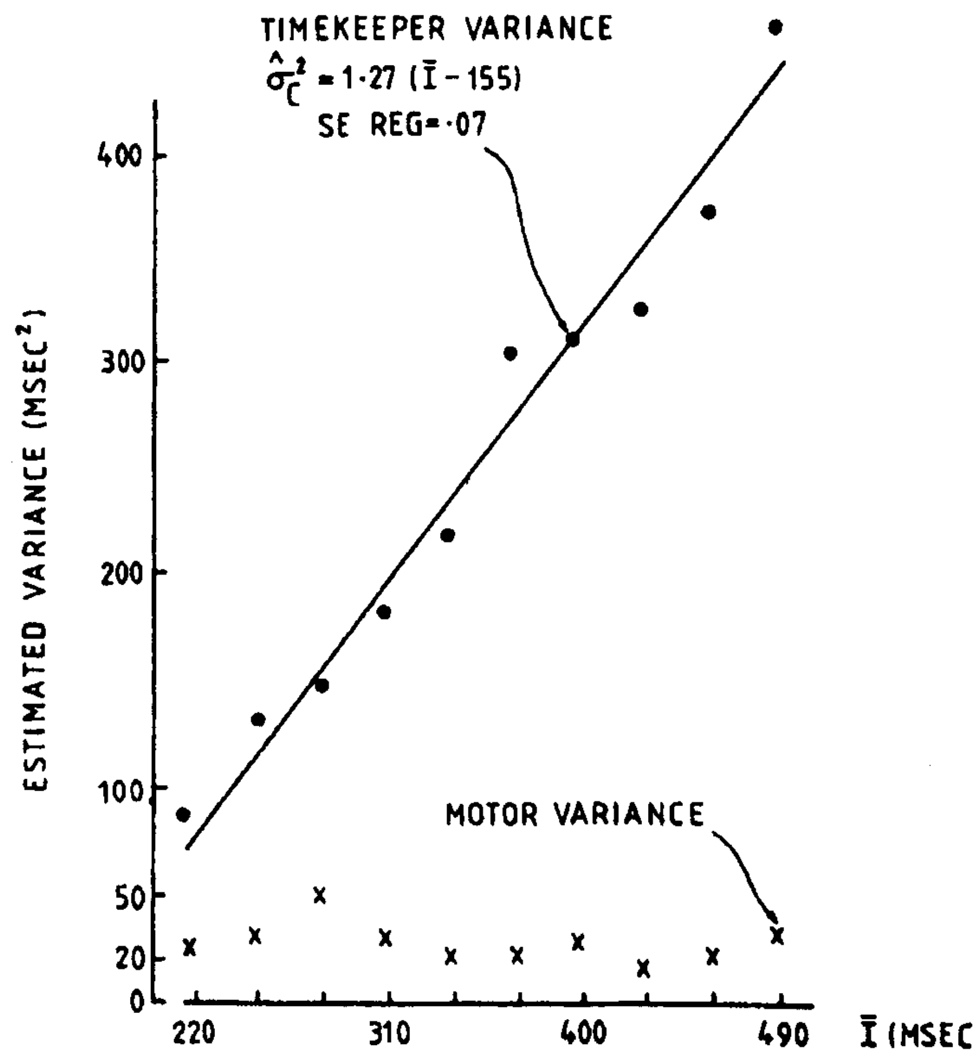
relative phase=DT/T

Absolute timing

- examples: music, prediction, estimating time
- typical task: tapping
- self-paced vs. externally paced

human performance

- on absolute timing is impressive
- smaller variance than 5% of cycle time in continuation paradigm



[Wing, 1980]

Theoretical account for absolute timing

- (neural) oscillator autonomously generates timing signal, from which timing events emerge
- => limit cycle oscillators
- Clocks=limit cycle oscillators

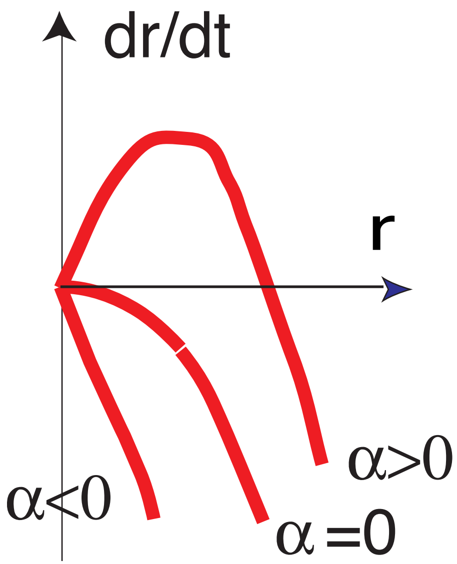
Limit cycle oscillator: Hopf

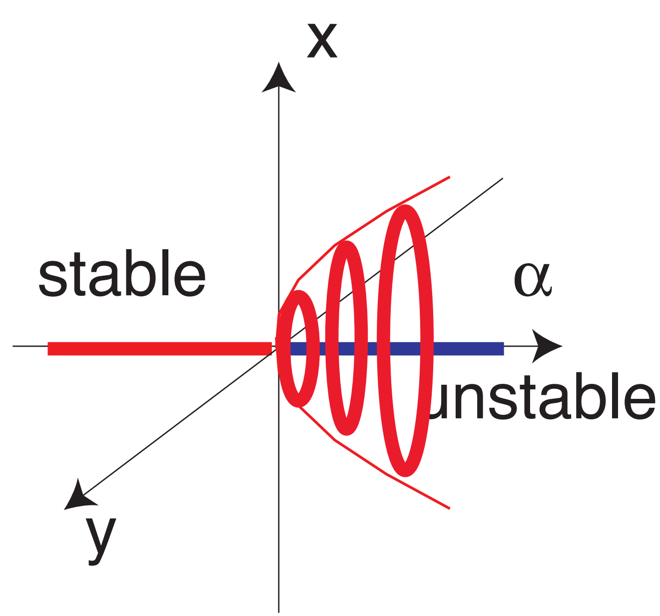
- normal form

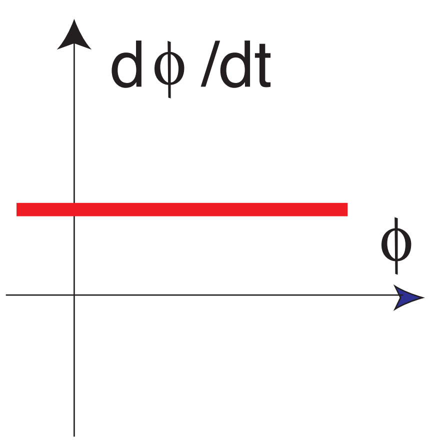
$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} \alpha & -\omega \\ \omega & \alpha \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} - (x^2 + y^2) \begin{pmatrix} x \\ y \end{pmatrix}$$

$$x = r\cos(\phi) \qquad \dot{r} = \alpha r - r^3$$

$$y = r\sin(\phi) \qquad \dot{\phi} = \omega$$







$$x(t) = \sqrt{\alpha}\sin(\omega t)$$

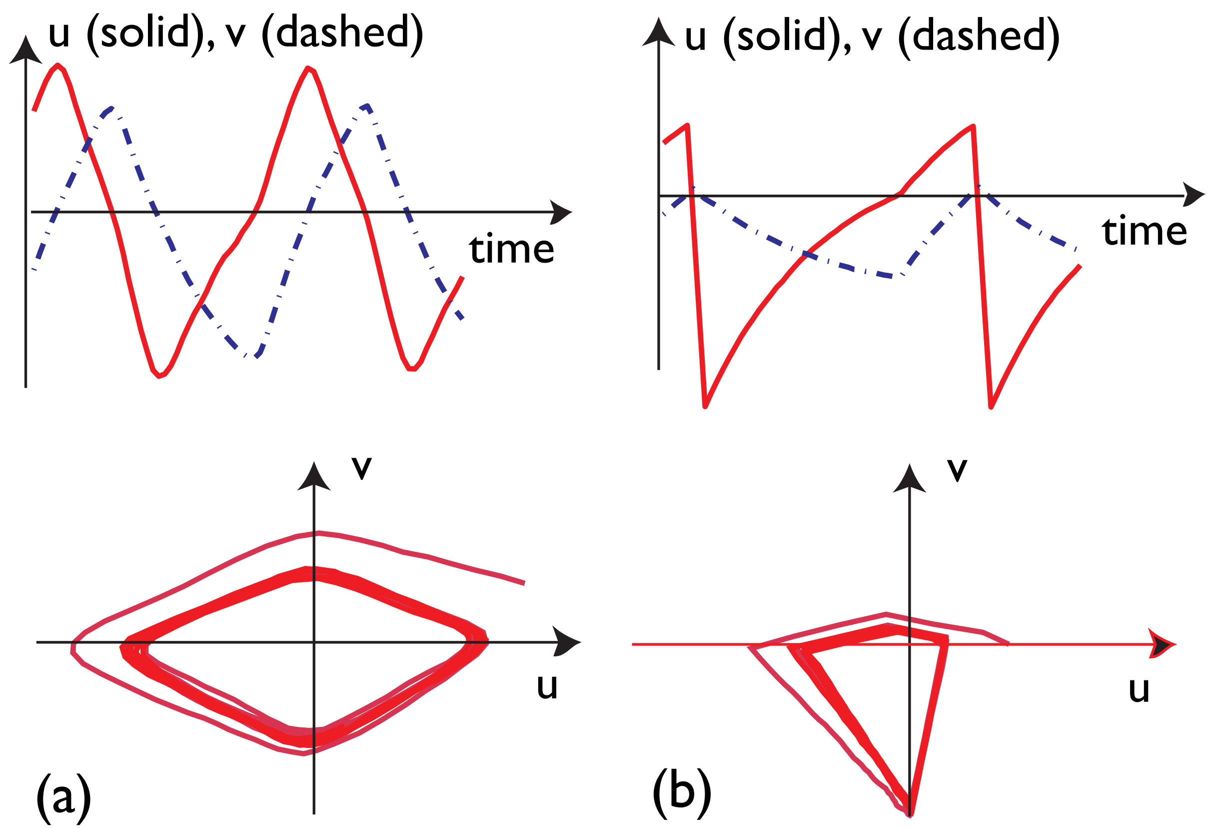
$$\text{amplitude } A = \sqrt{\alpha}$$

$$\text{cycle time } T = 2\pi/\omega,$$

Neural oscillator

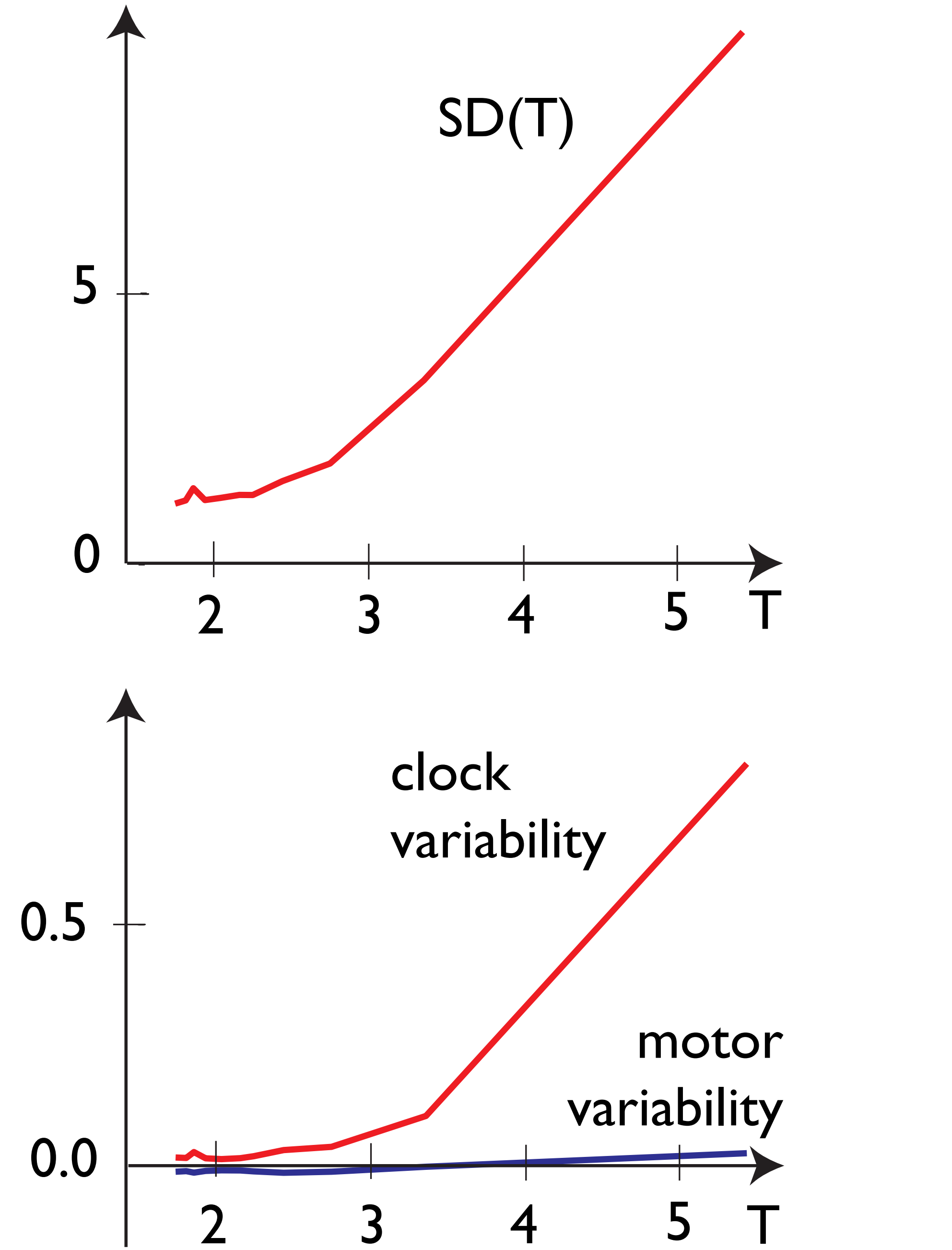
- relaxation oscillator

$$\tau \dot{u} = -u + h_u + w_{uu} f(u) - w_{uv} f(v)$$
$$\tau \dot{v} = -v + h_v + w_{vu} f(u),$$



[Amari 77]

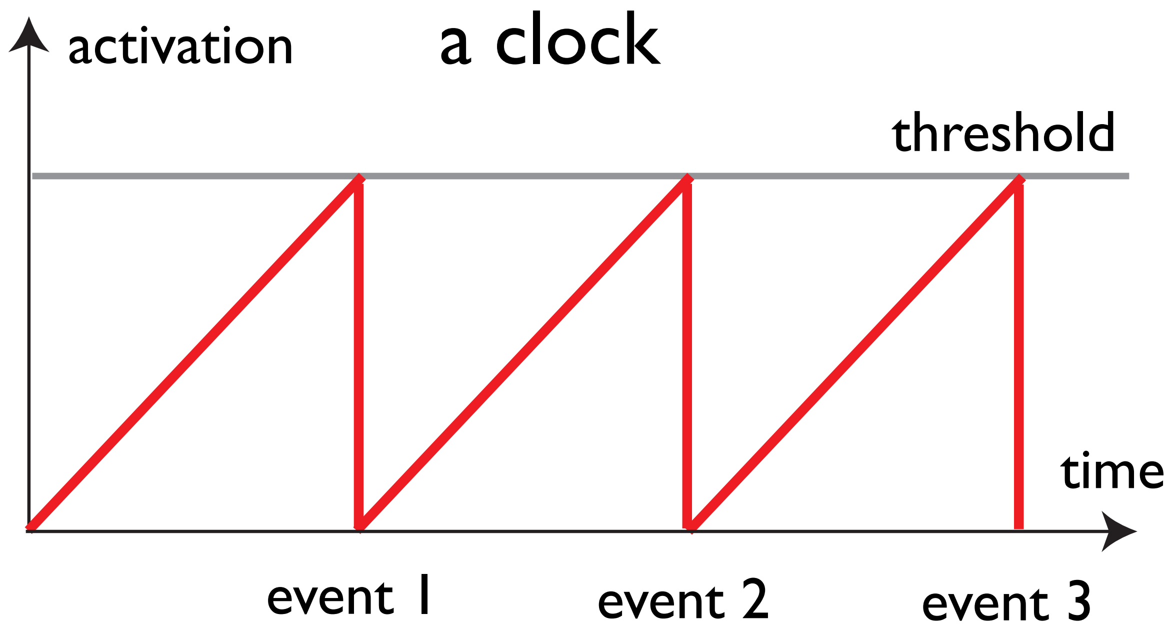
Neural oscillator accounts for variance of absolute timing



[Schöner 2002]

Clocks

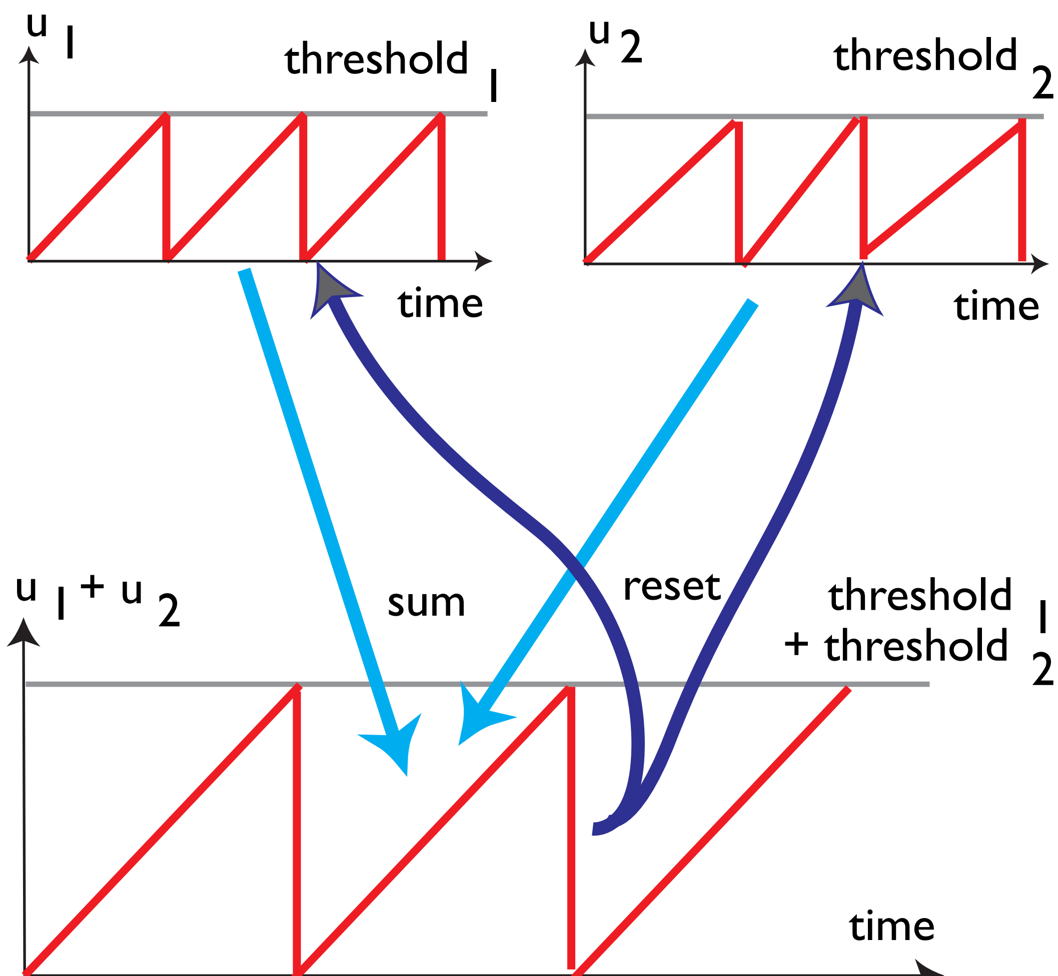
- hour glasses are also oscillators
- but: it is critical to include the “resetting”



[from: Schöner, Brain & Cogn 48:31 (2002)]

Reduced timing variance for bimanual movement

- observed by Ivry and colleagues
- accounted for by averaging of two times
- but: requires coupling



Relative timing: movement coordination

- locomotion, interlimb and intralimb
- speaking
- mastication
- music production
- ... approximately rhythmic

Examples of coordination of temporally discrete acts:

- reaching and grasping
- bimanual manipulation
- coordination among fingers during grasp
- catching, intercepting

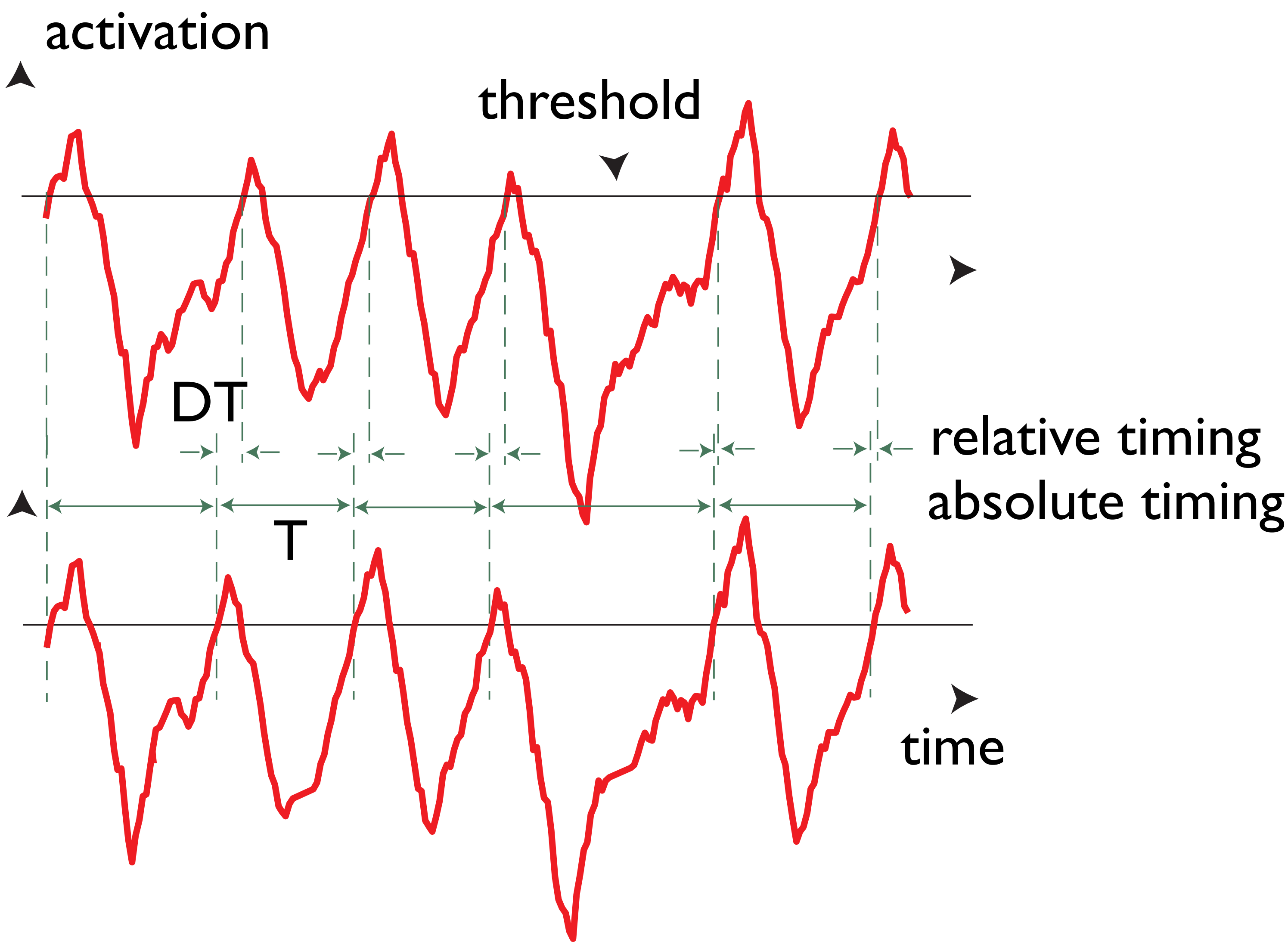
Definition of coordination

- Coordination is the maintenance of stable timing relationships between components of voluntary movement.
- Operationalization: recovery of coordination after perturbations
- Example: speech articulatory work (Gracco, Abbs, 84; Kelso et al, 84)
- Example: action-perception patterns

Is movement always timed/ coordinated?

- No, for example:
- locomotion: whole body displacement in the plane
  - in the presence of obstacles takes longer
  - delay does not lead to compensatory acceleration
- but coordination is pervasive...
  - e.g., coordinating grasp with reach

Relative vs. absolute timing



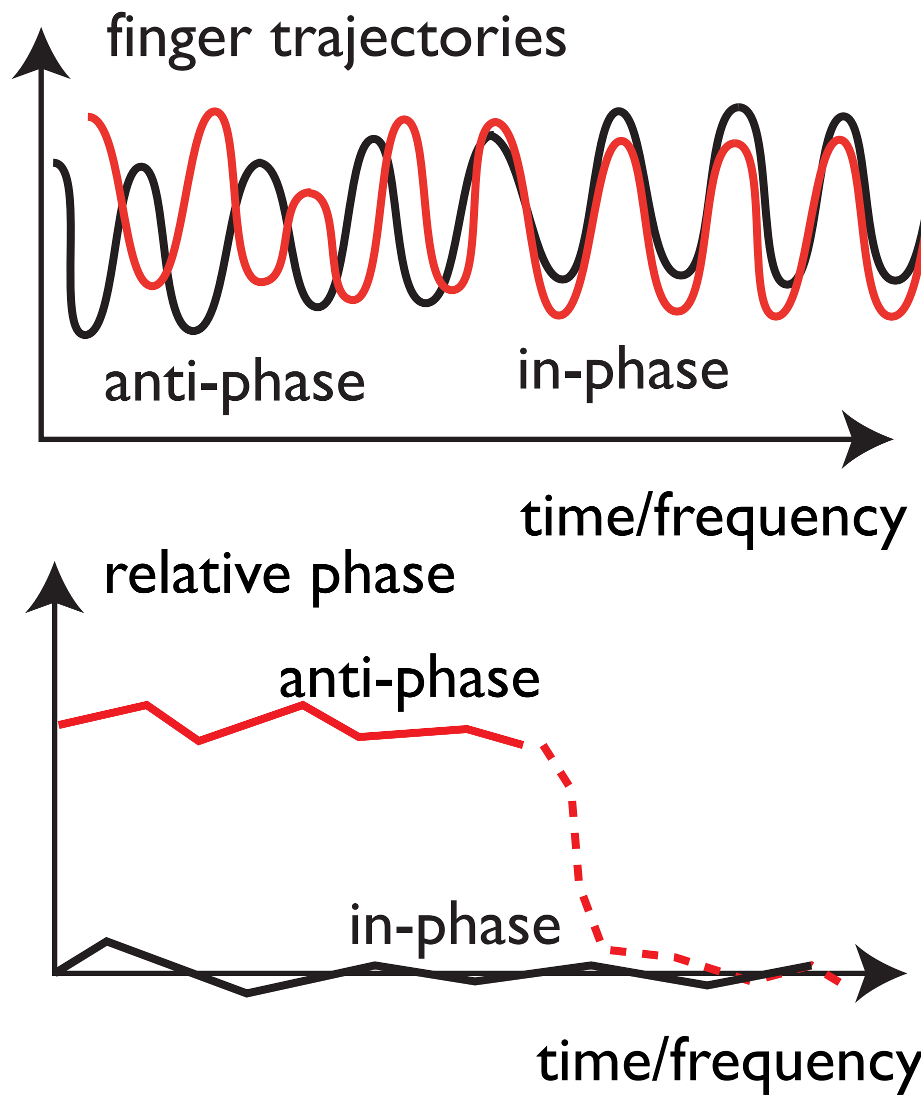
relative phase=DT/T

Two basic patterns of coordination

- in-phase
  - synchronization, moving through like phases simultaneously
  - e.g., gallop (approximately)
- anti-phase or phase alternation
  - syncopation
  - e.g., trott

An instability in rhythmic movement coordination

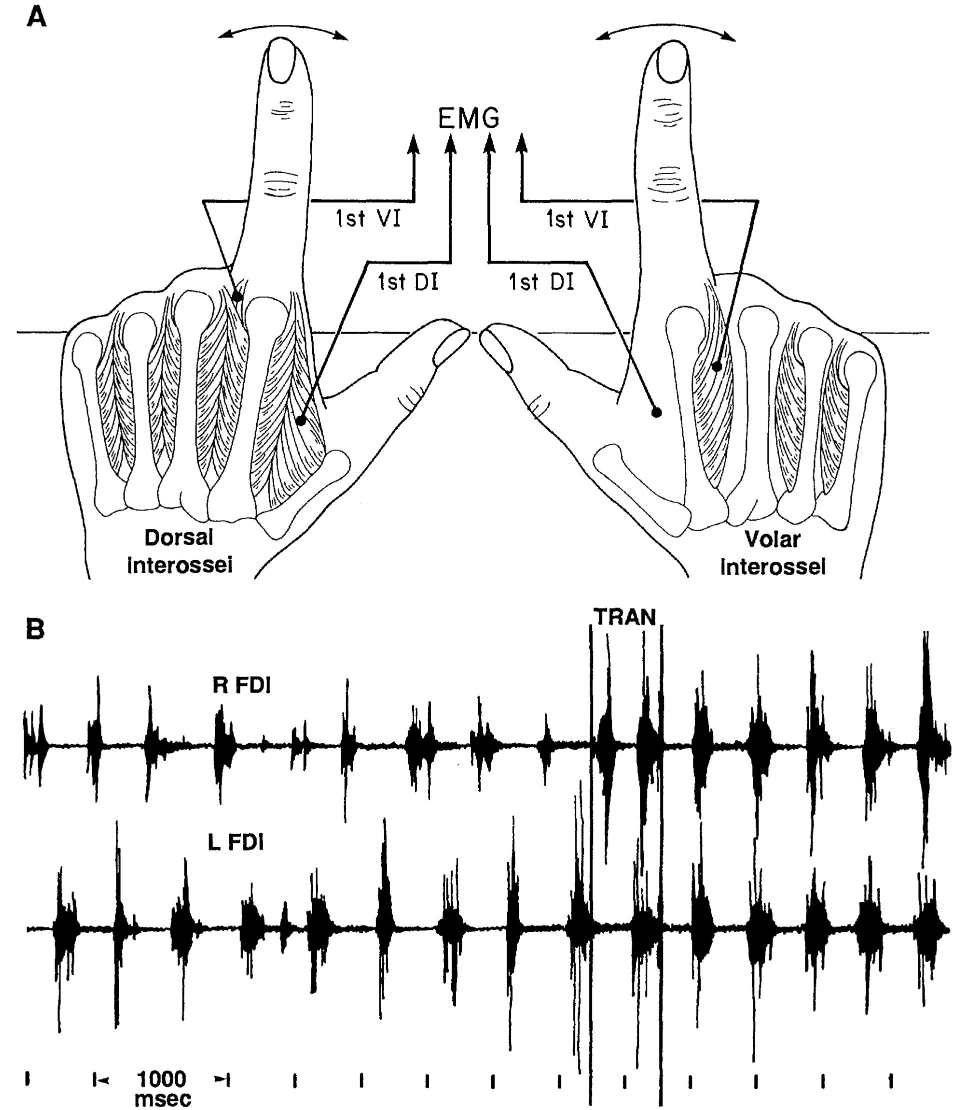
- switch from anti-phase to in-phase as rhythm gets faster



Kelso, 1984

Instability

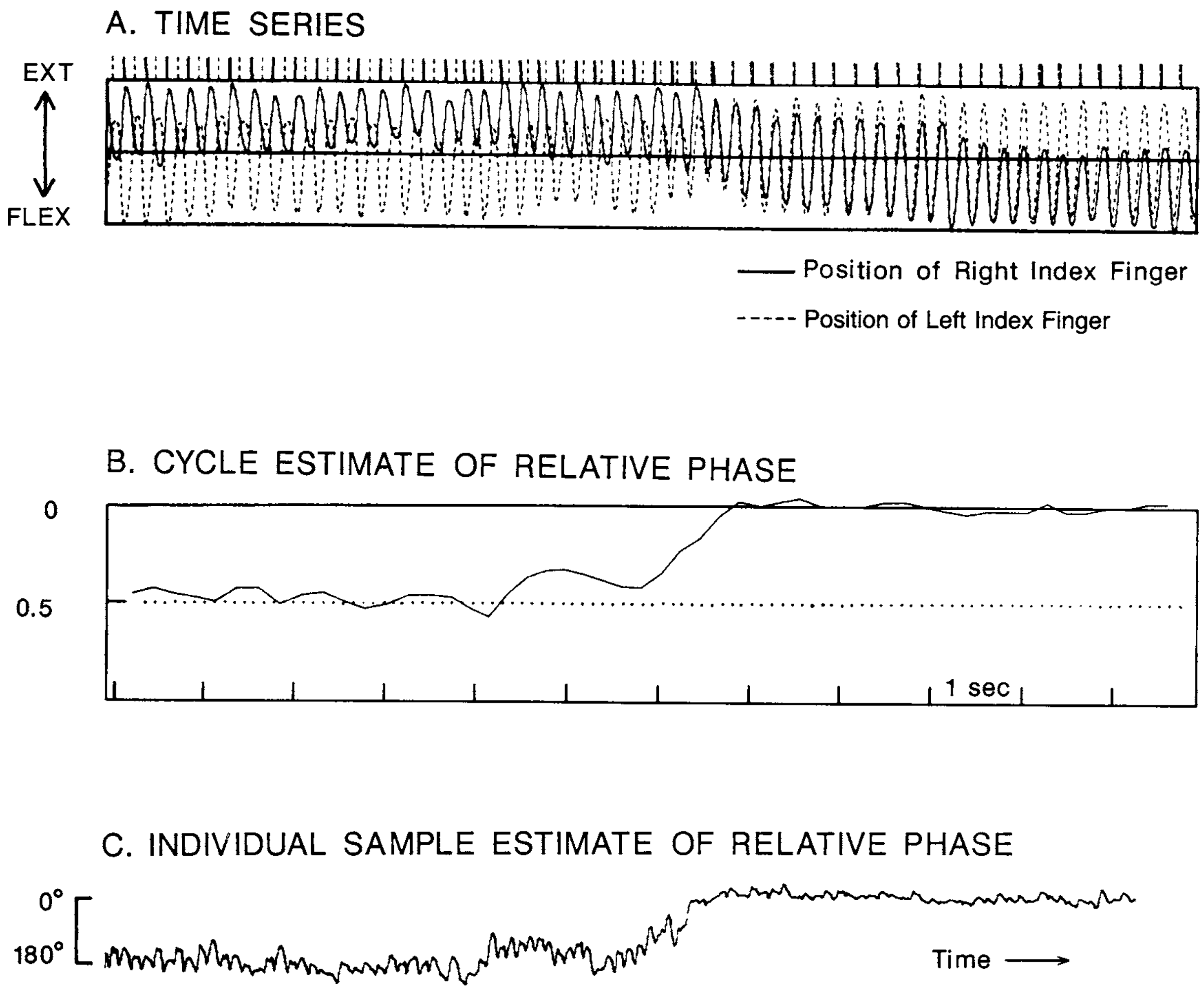
- experiment involves finger movement
- why fingers?
  - no mechanical coupling
  - constraint of maximal frequency irrelevant
  - => pure neurallly based coordination



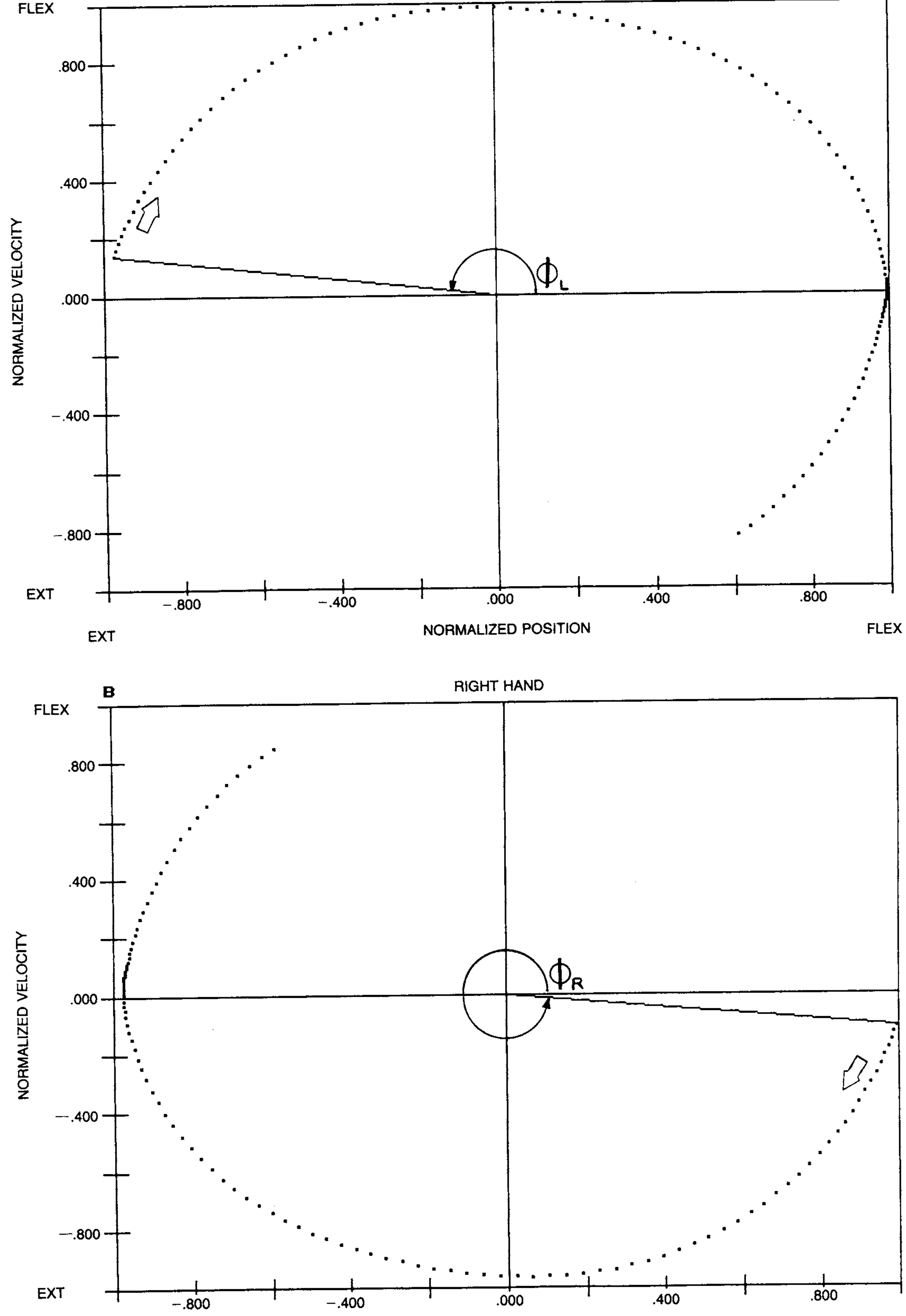
Schöner, Kelso (Science, 1988)

Instability

- frequency imposed by metronomes and varied in steps
- either start out in-phase or anti-phase



data example (Scholz, 1990)



computation of continuous relative phase (Scholz, 1990)

Pattern stability

- instability: anti-phase pattern no longer persists
- thus: even though mean pattern is unchanged up to transition, its stability is lost
- => stability is an important property of coordination patterns, that is not captured by the mean performance alone

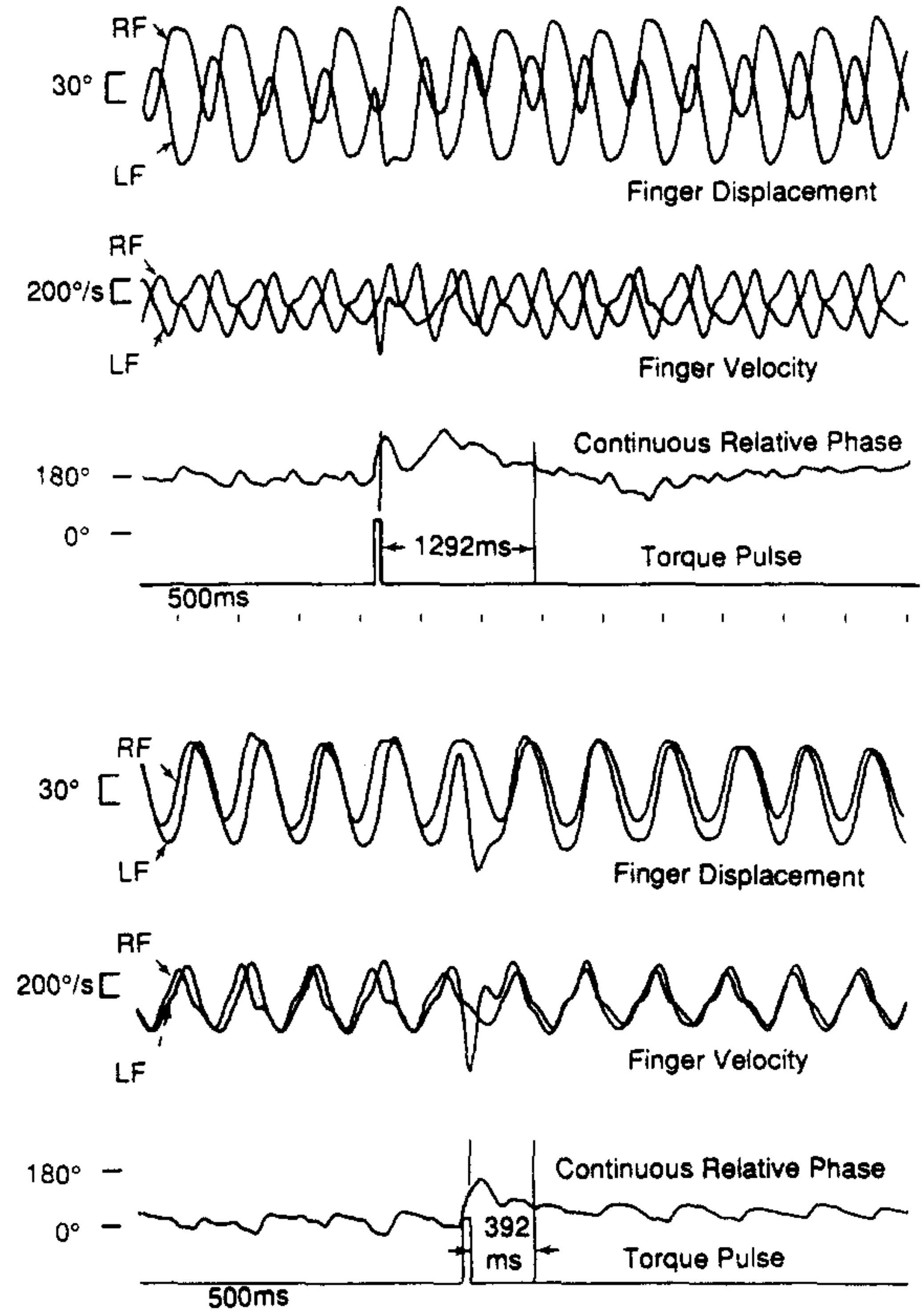
Measures of stability

- variance: fluctuations in time are an index of degree of stability
    - stochastic perturbations drive system away from the coordinated movement
    - the less resistance to such perturbations, the larger the variance

Measures of stability

- relaxation time
  - time need to recover from an outside perturbation
  - e.g., mechanically perturb one of the limbs, so that relative phase moves away from the mean value, then look how long it takes to go back to the mean pattern
  - the less stable, the longer relaxation time

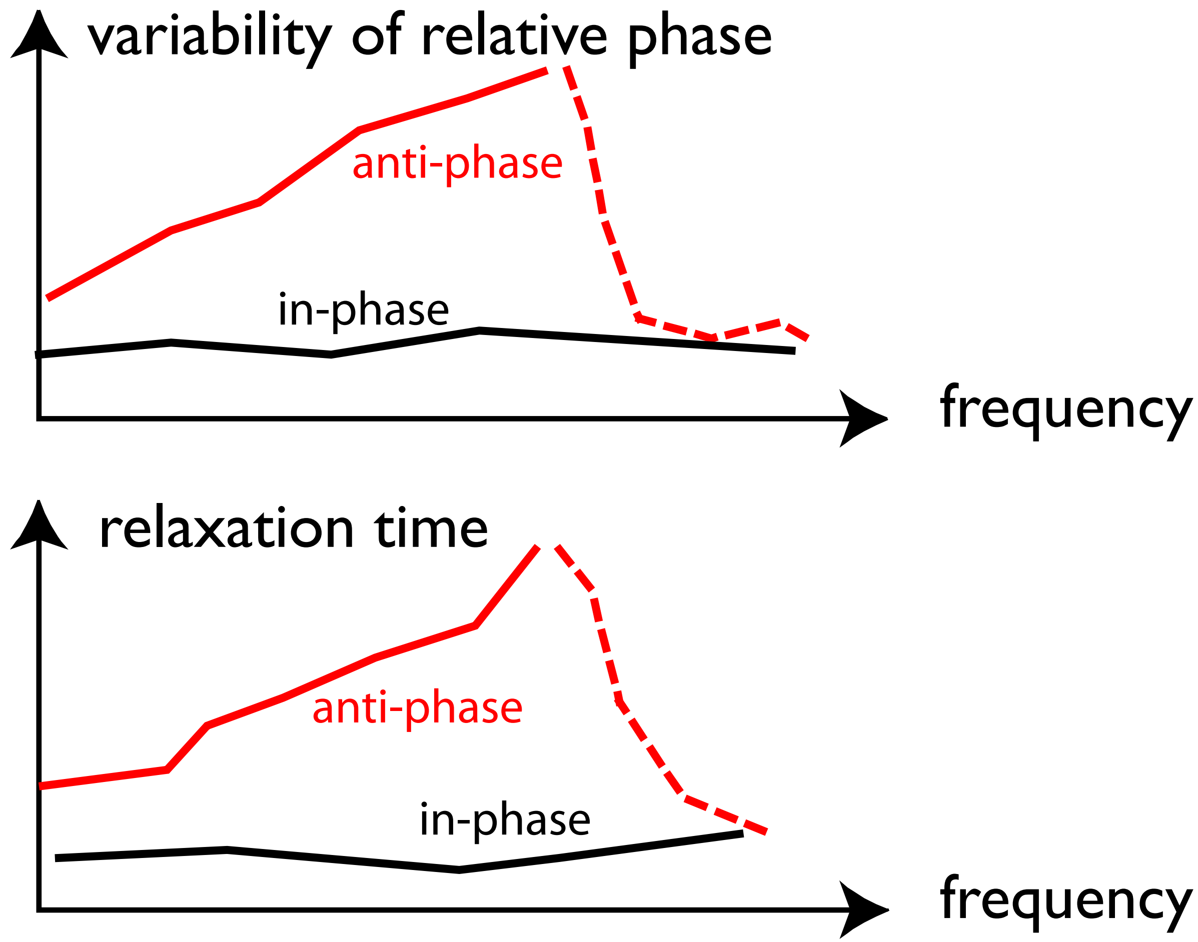
data example
perturbation of
fingers and
relative phase

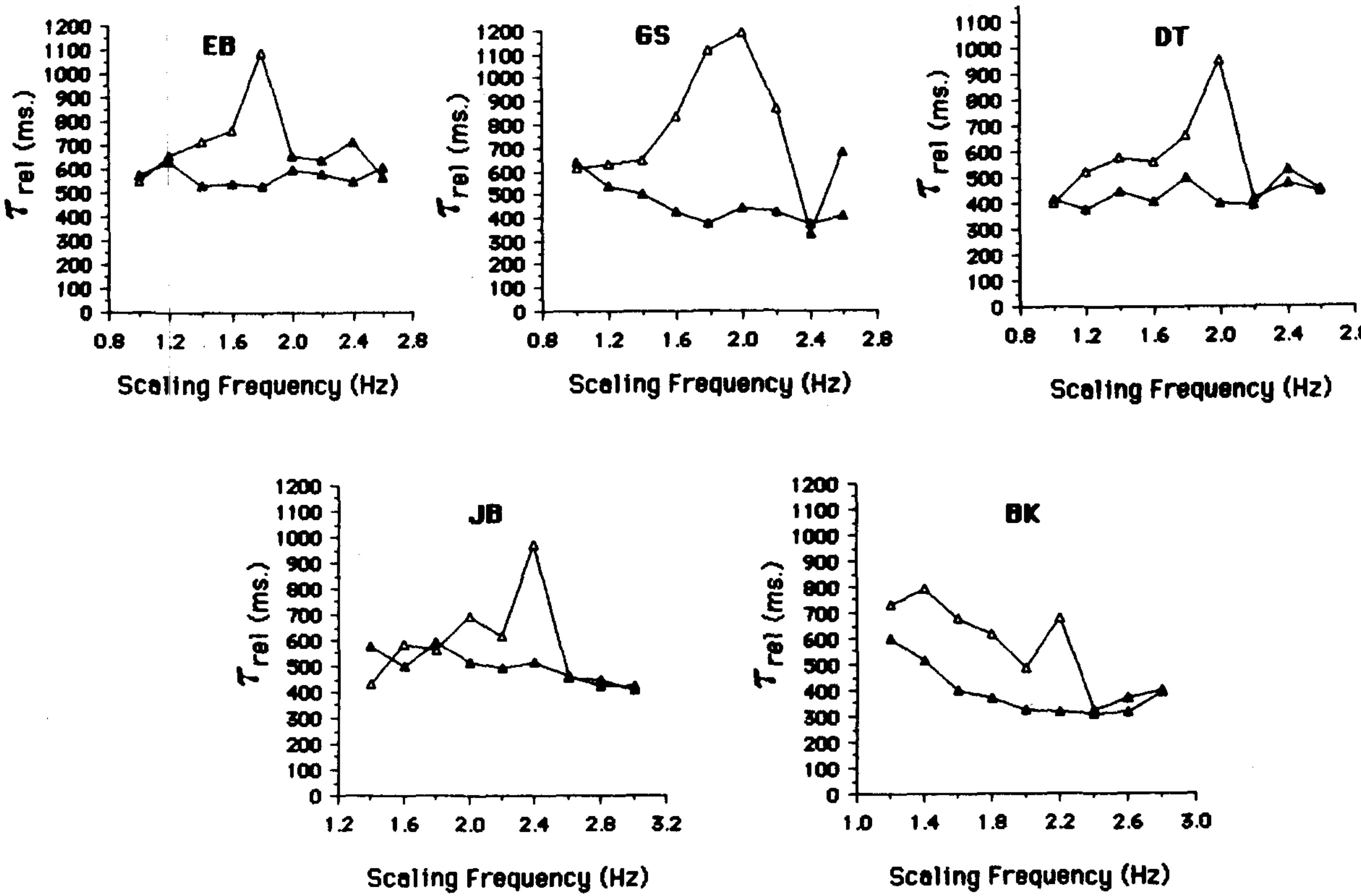


Scholz, Kelso, Schöner, 1987

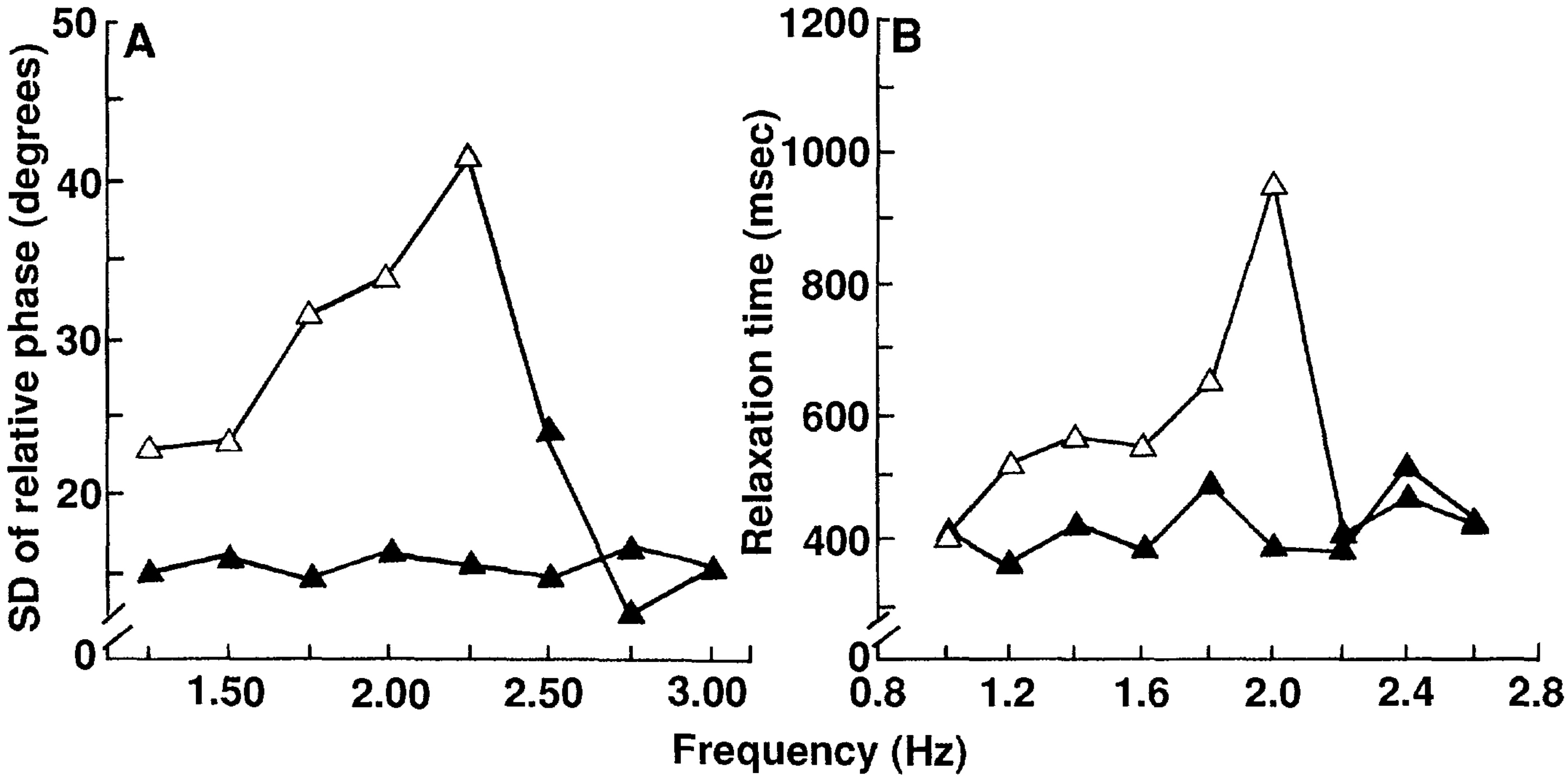
Signatures of instability

- loss of stability indexed by measures of stability





relaxation times, individual data



data (averaged across subjects)

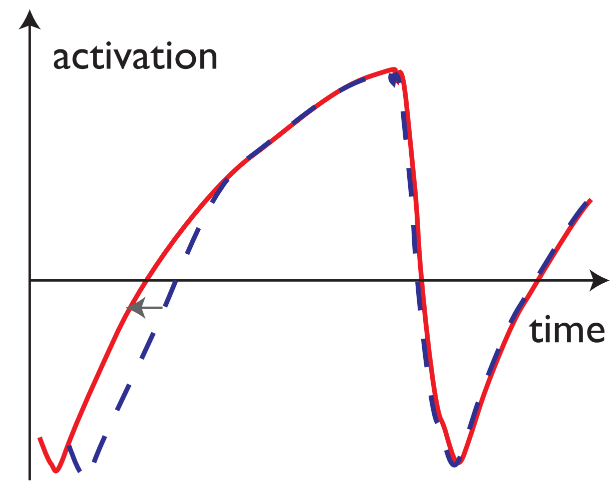
Schöner, Kelso (Science, 1988)

Neuronal process for coordination

- each component is driven by a neuronal oscillator
- their excitatory coupling leads to in-phase
- their inhibitory coupling leads to anti-phase

Coordination from coupling

- coordination=stable relative timing emerges from coupling of neural oscillators

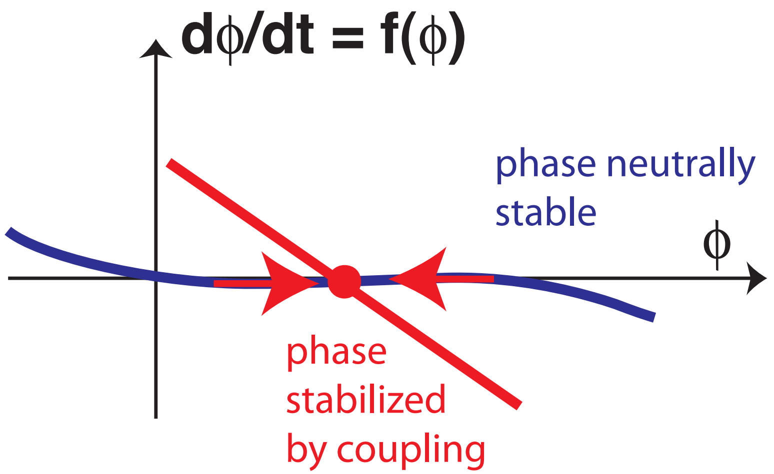


$$\tau \dot{u}_1 = -u_1 + h_u + w_{uu} f(u_1) - w_{uv} f(v_1)$$
$$\tau \dot{v}_1 = -v_1 + h_v + w_{vu} f(u_1) \boxed{+ c f(u_2)}$$
$$\tau \dot{u}_2 = -u_2 + h_u + w_{uu} f(u_2) - w_{uv} f(v_2)$$
$$\tau \dot{v}_2 = -v_2 + h_v + w_{vu} f(u_2) \boxed{+ c f(u_1)}$$

[Schöner: Timing, Clocks, and Dynamical Systems. *Brain and Cognition* 48:31-51 (2002)]

Movement timing

- marginal stability of phase enables stabilizing relative timing while keeping trajectory unaffected



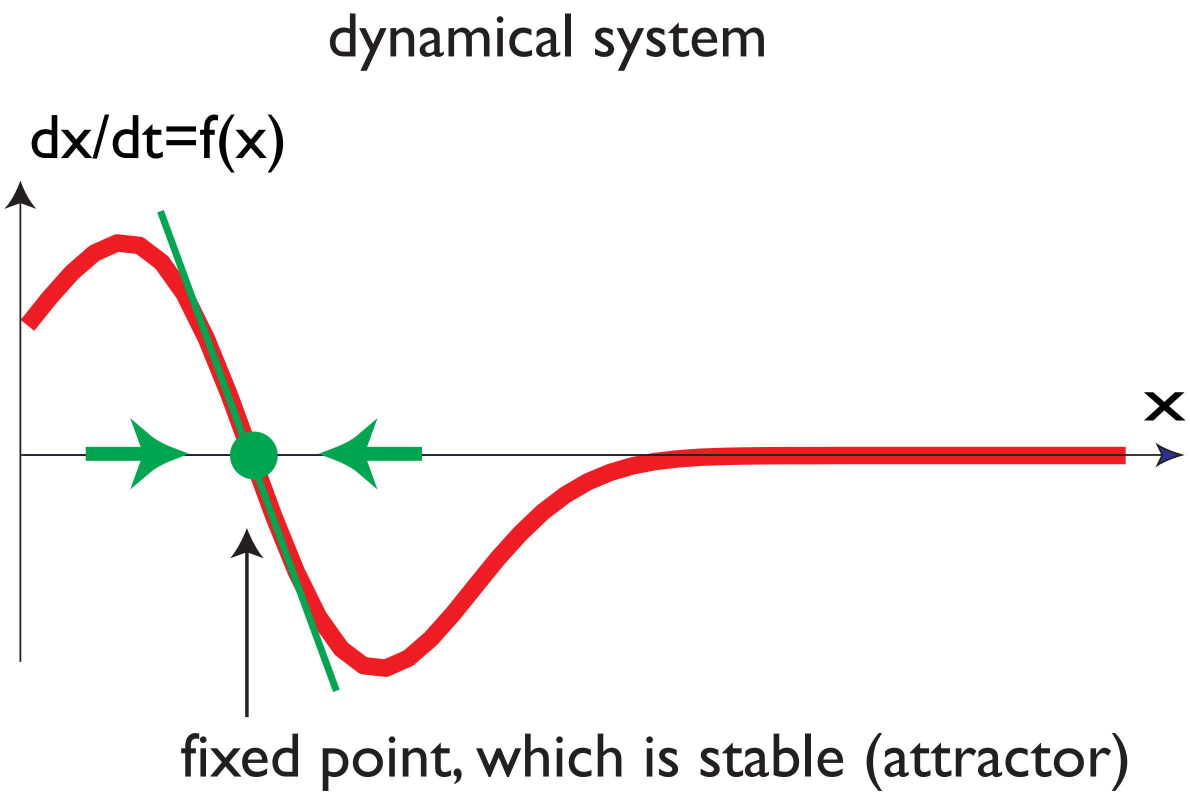
[Schöner: Timing, Clocks, and Dynamical Systems. *Brain and Cognition* 48:31-51 (2002)]

Dynamical systems account of instability

- coordination patterns are stable states
- stability may vary and may be lost
- instability leads to pattern change

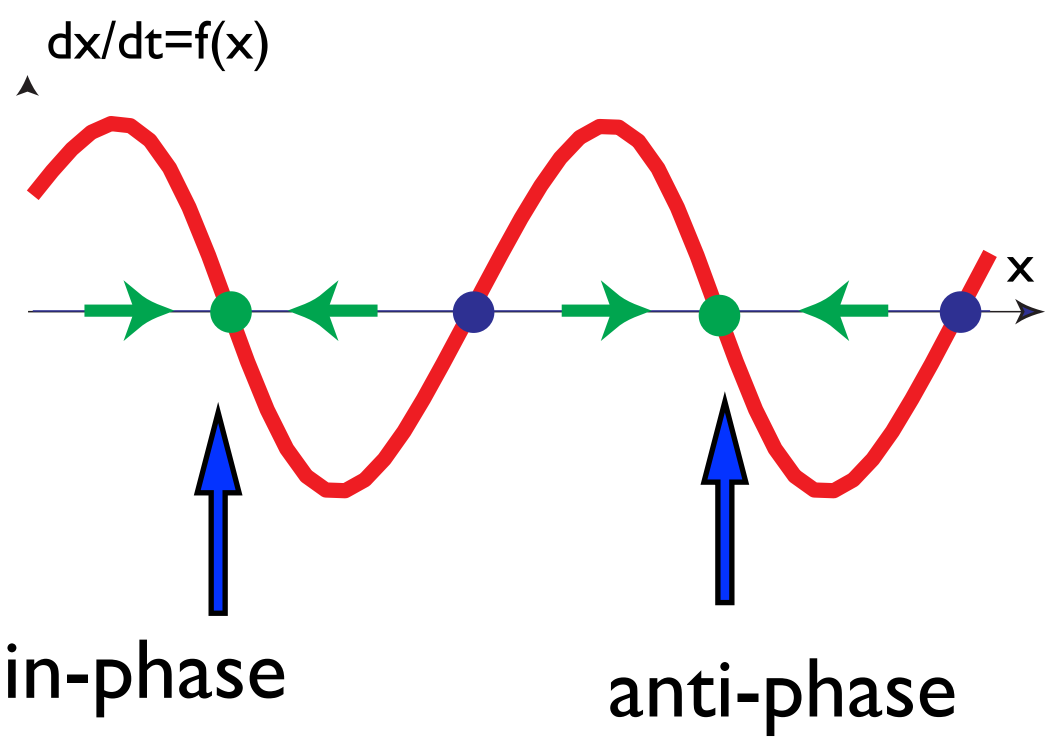
Dynamical systems account of instability

- state of dynamical system x=relative phase



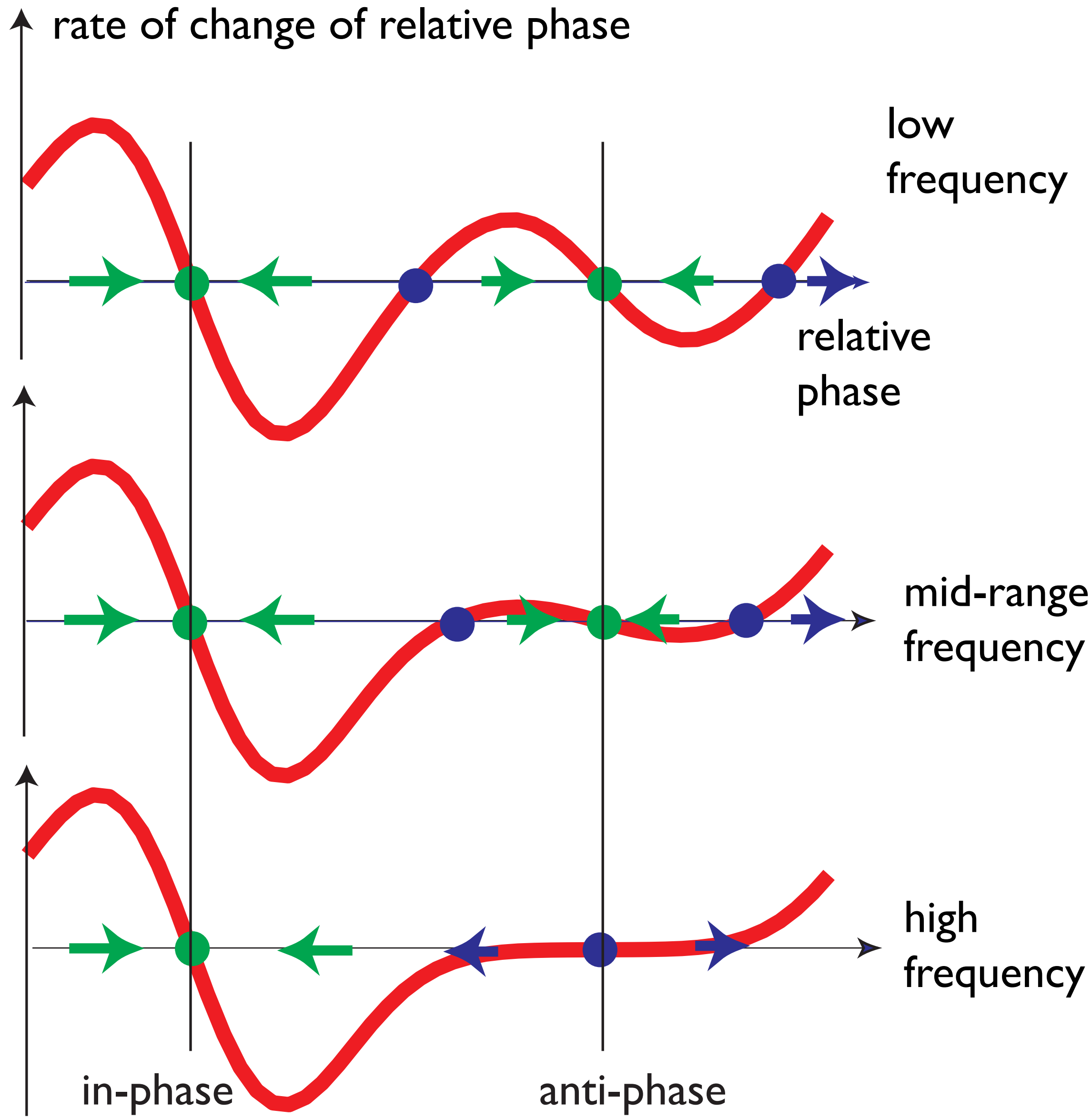
Dynamical systems account of instability

- at low frequencies this system is bistable

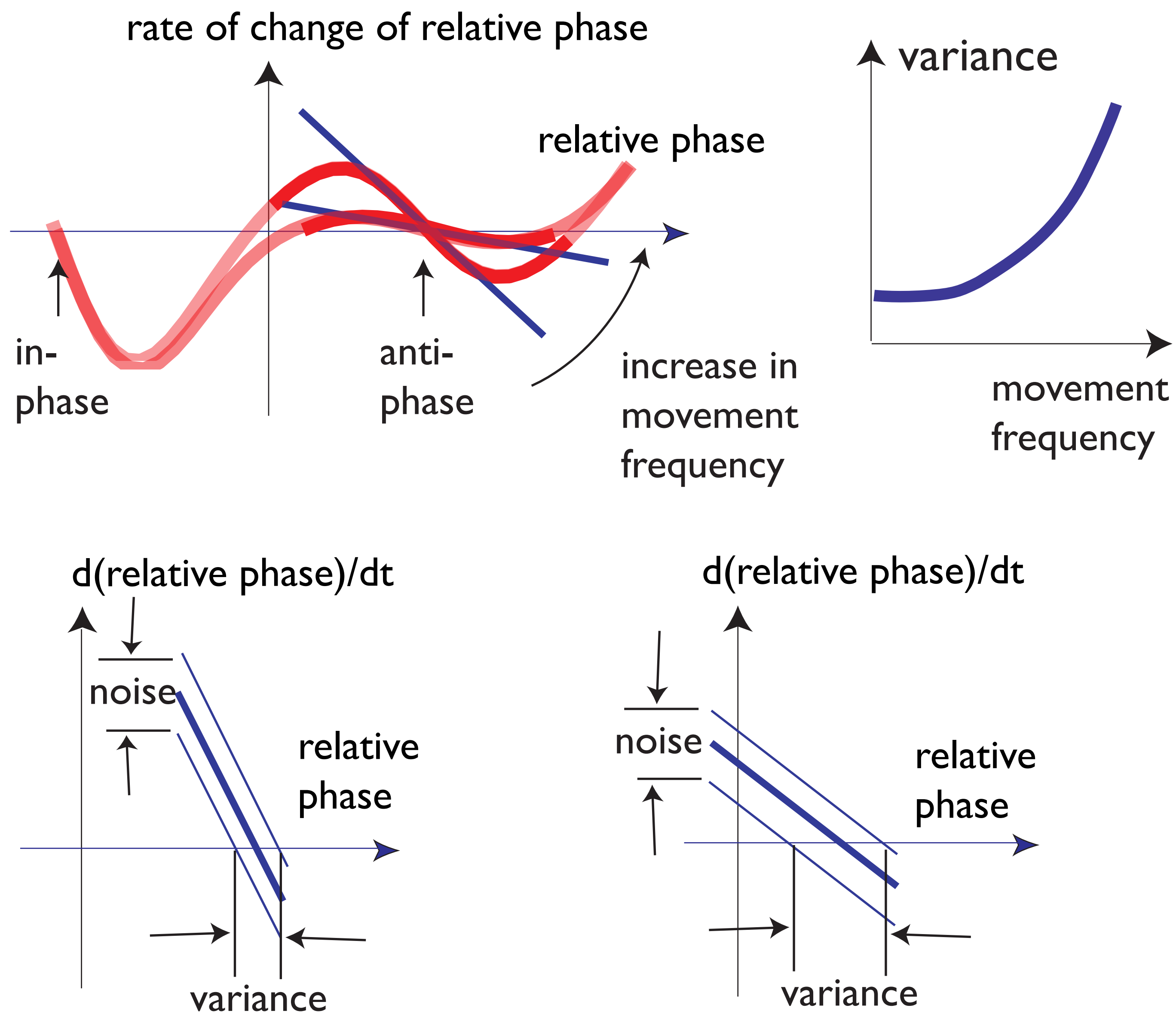


Dynamical systems account of instability

- at increasing frequency stability of anti-phase is lost



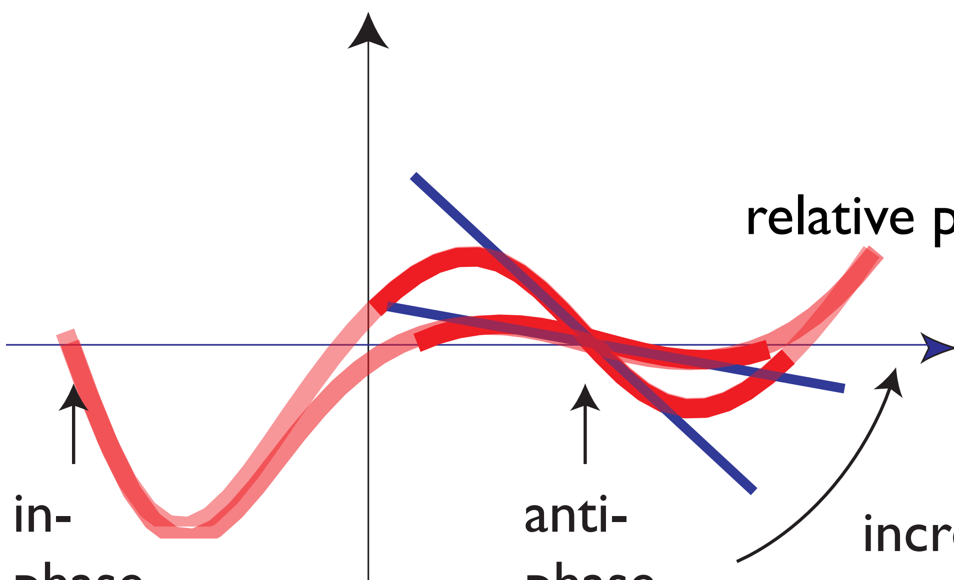
Predicts increase in variance

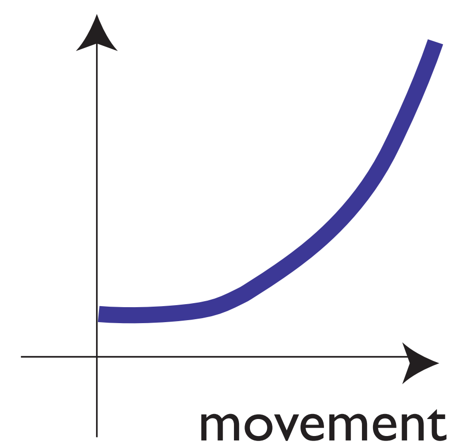


- "critical fluctuations"

Predicts increase in relaxation time

- “critical slowing down”





Conclusion

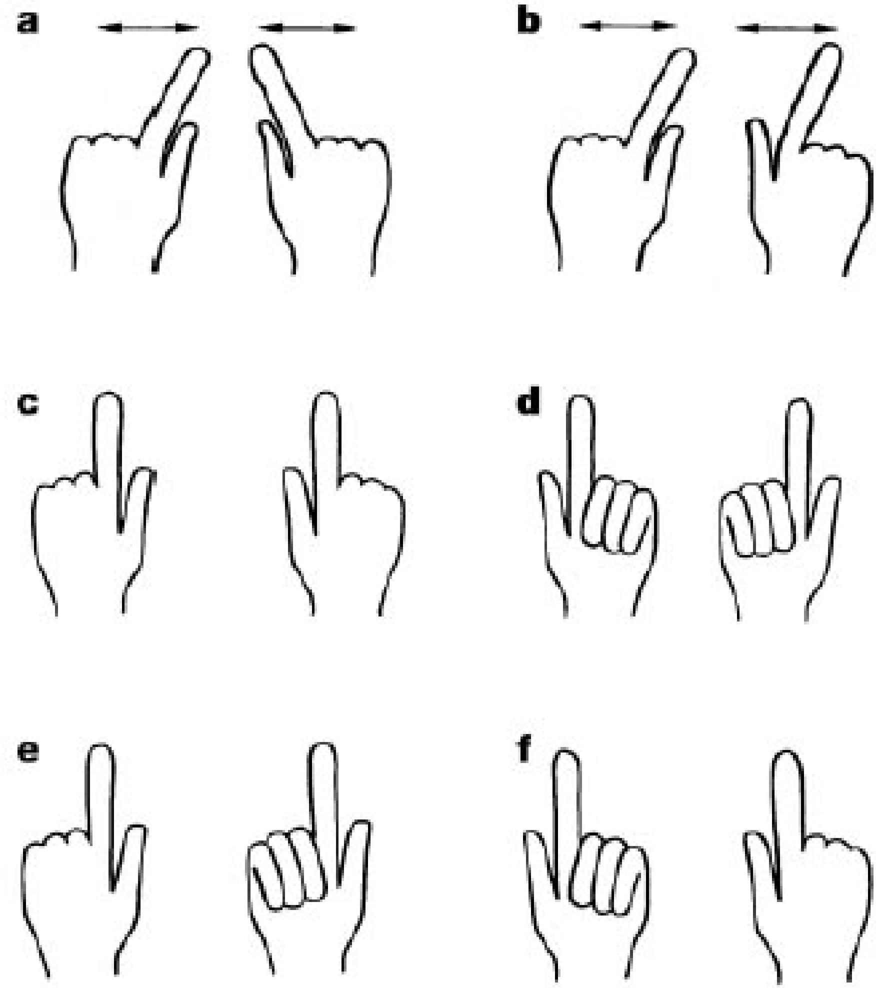
- to understand coordination patterns, we need to understand the underlying coordination dynamics
- = stabilization mechanisms
- and their strength
- from which the mean pattern emerges

What level does the instability of coordination come from?

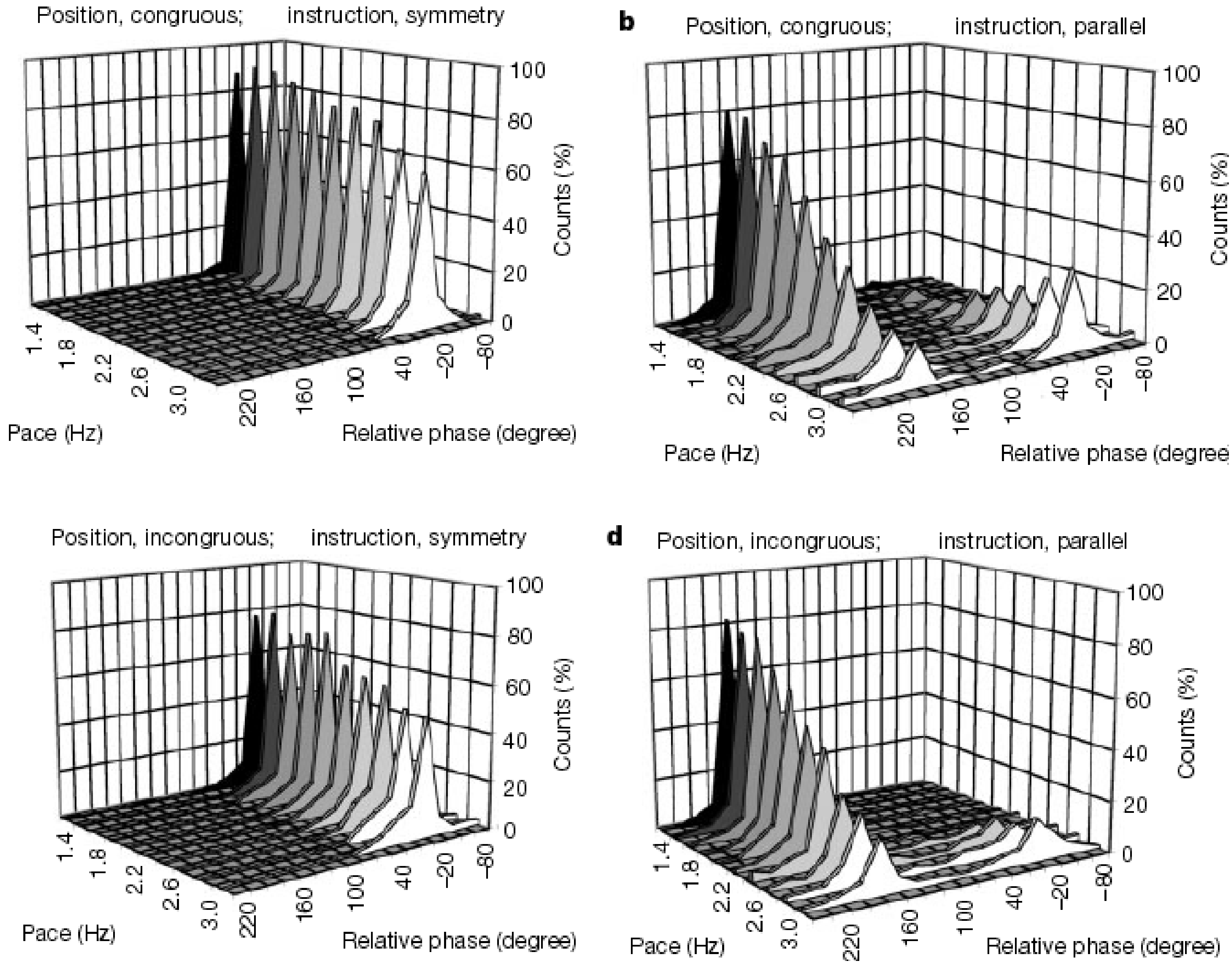
- from peripheral motor control?
- from central motor control?
- from perceptual representations of movement?

What level does instability come from?

Is the instability tied to the motor system?



Mechsner, Kerzel, Knoblich, Prinz, Nature 2001



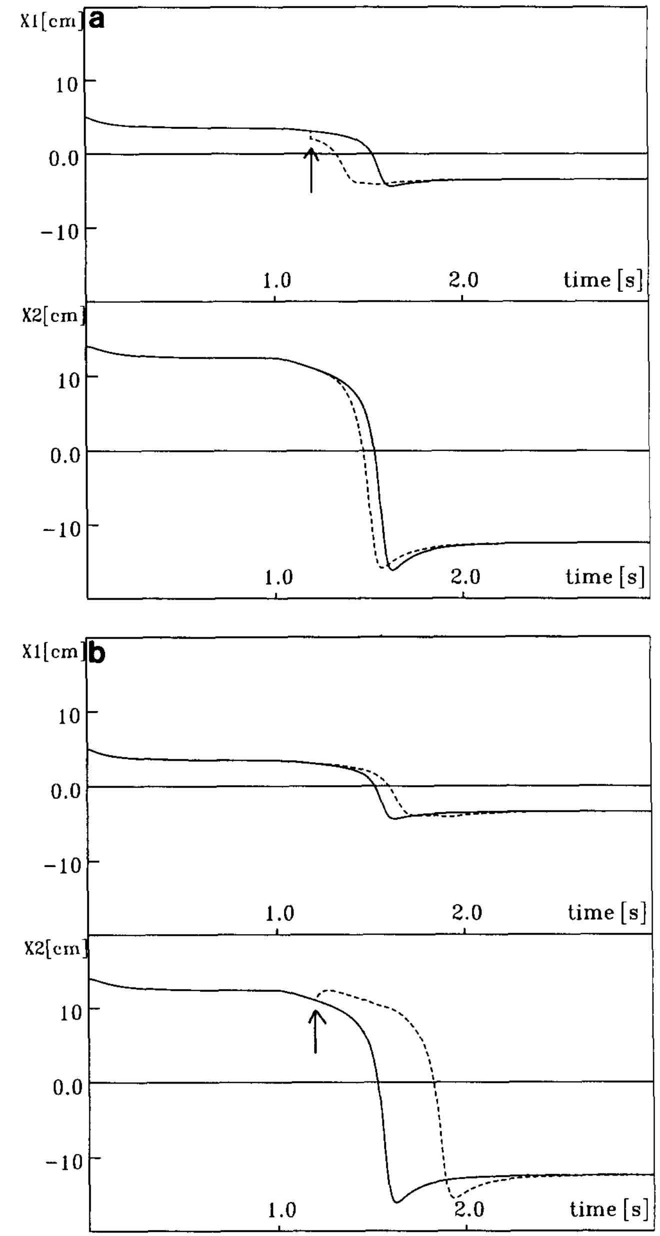
Mechsner, Kerzel, Knoblich, Prinz, Nature 2001

=> coordination in space

- rather than in effector space
- so coordinated oscillators are central
- rather than peripheral

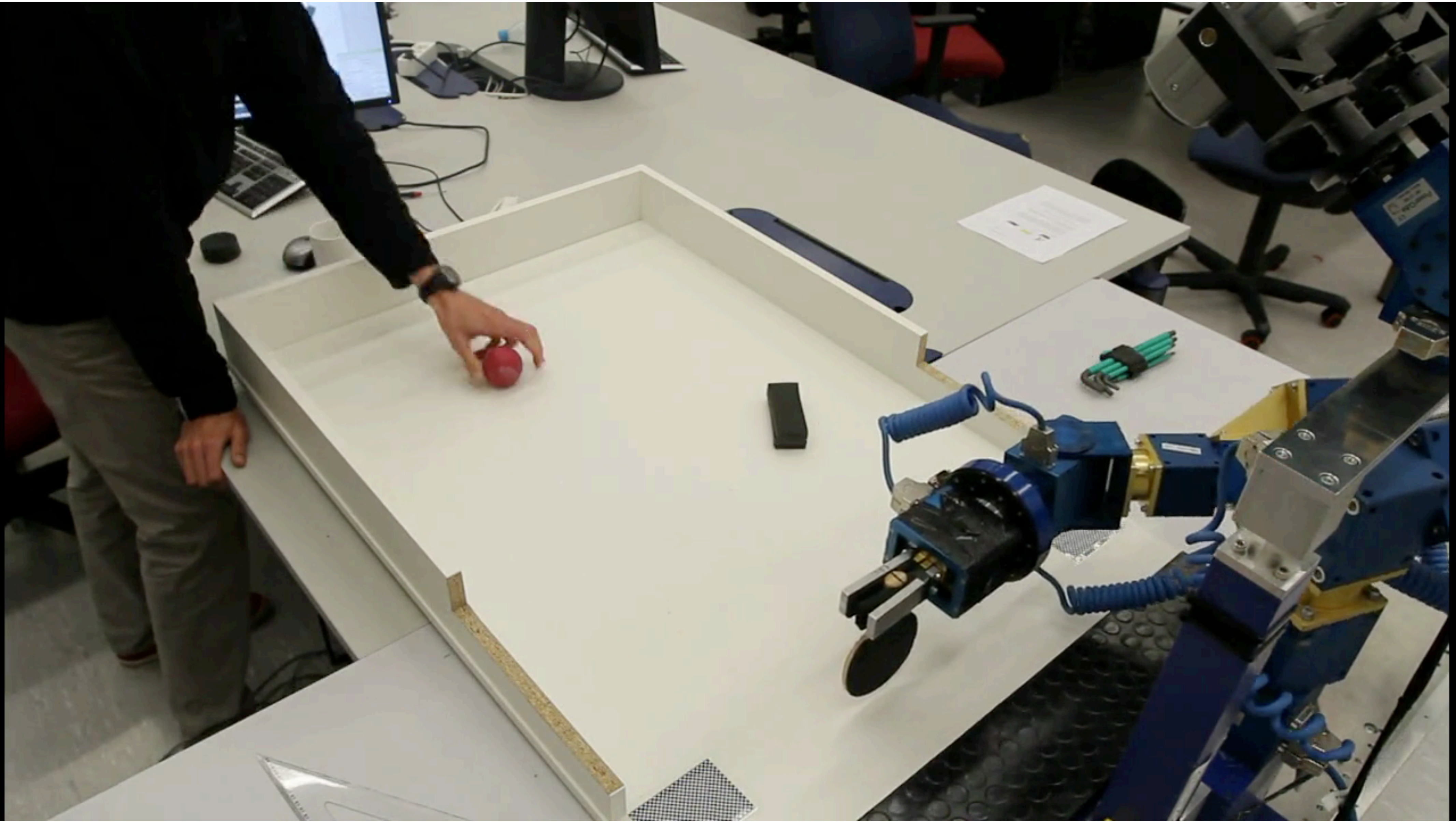
Coordination of discrete movement

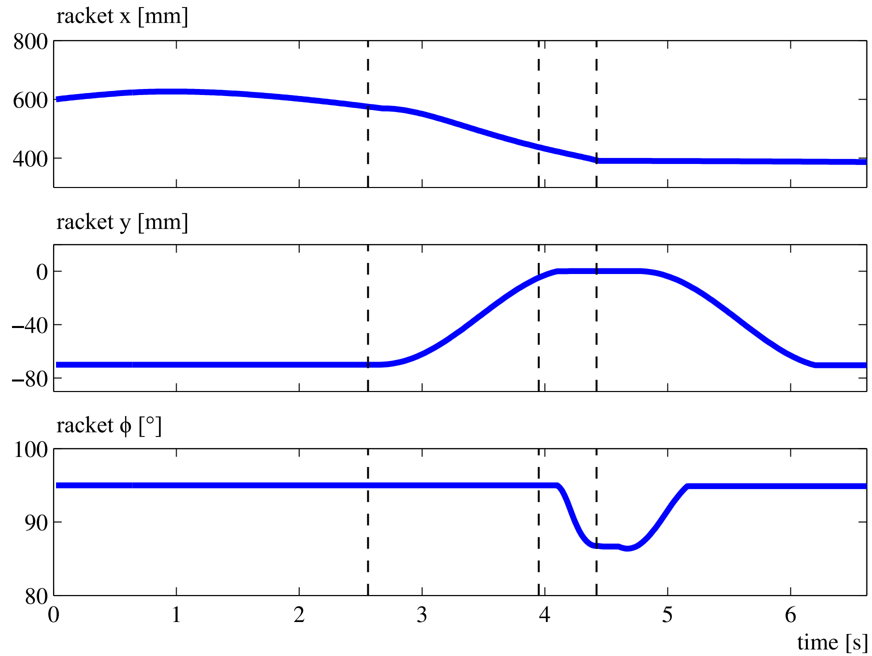
- coupling can account for coordination of discrete movement based on the idea that oscillator is "on" (stable) only for a cycle…
- back and forth components of rhythmic movement are driven by different neural populations
    - so even rhythmic movement coordination may exploit this mechanism of discrete movement coordination

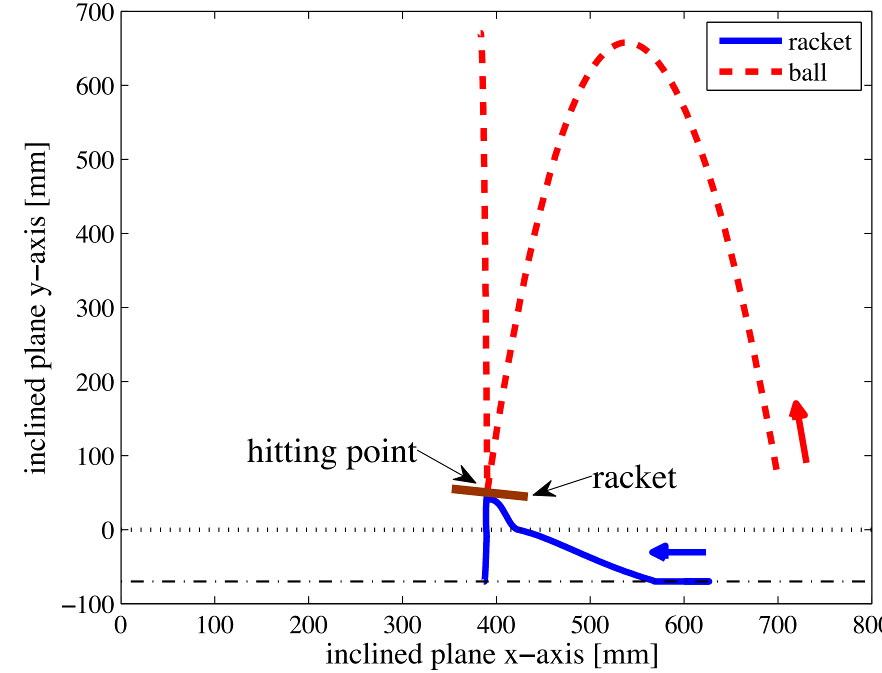


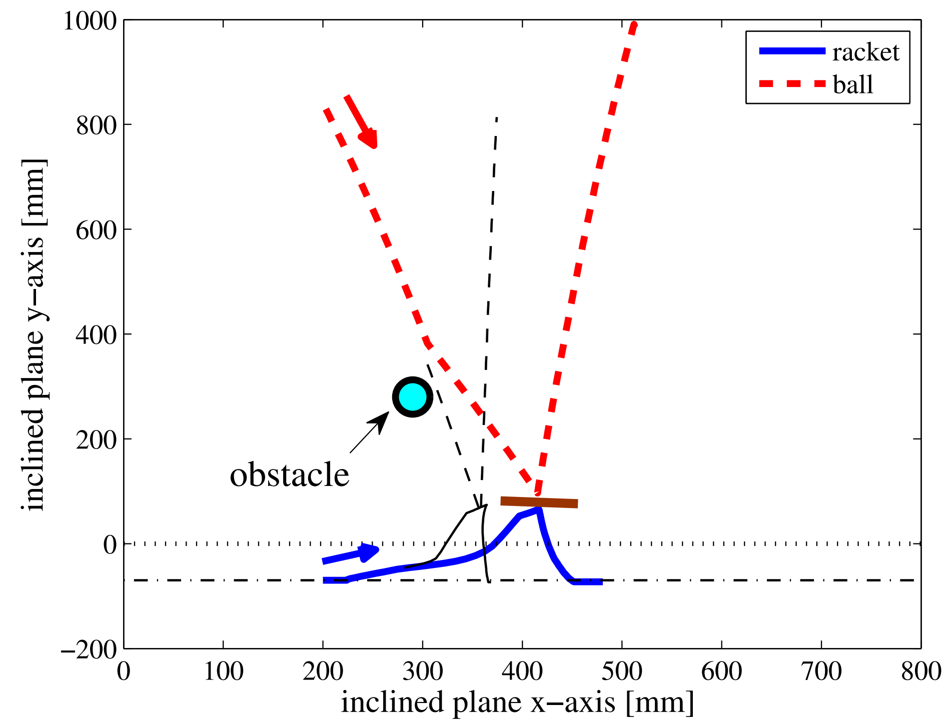
[Schöner, Biol Cybern 63:257 (1990)]

Robotic demonstration: timed movement with online updating









[Oubbati, Richter, Schöner, 2013]

… deeper issue in timing…

- contribution of the control level
  - muscles and biomechanics contribute to timing
- contribution of movement planning
  - on line updating
  - arriving "just in time"
- contribution of movement organization
  - timed movement sequences
  - modulating timing in rhythms
  - coarticulation