

# Timing and coordination

Gregor Schöner

# In vehicle motion planning

- movement is generated through a “behavioral dynamics” that is in closed loop with the environment
- taking into account (possibly time varying) constraints from the perceived environment
- time to reach the target was not a constraint.. and not controlled/stabilized

# Reaching movements of an arm

- reaching movements may be generated in open loop.. by an internal “neural” dynamics
- generate movements that are “timed”, that is,
  - they arrive “on time”
  - they are coordinated across different effectors
  - they are coordinated with moving objects (e.g., catching)
- timing implies some form of anticipation...

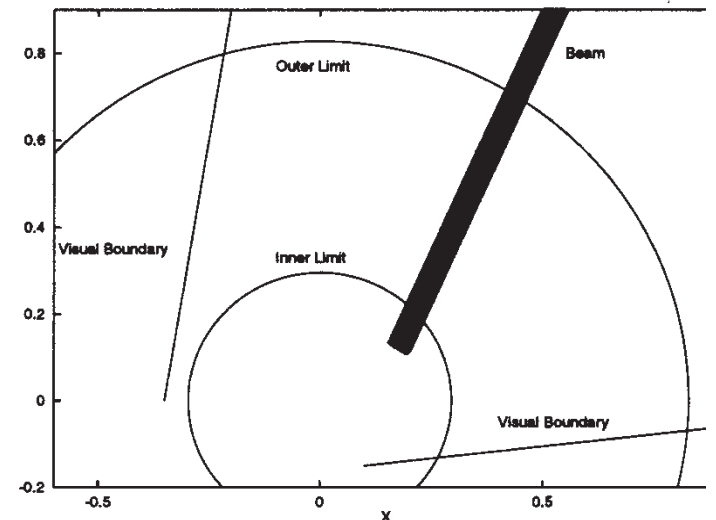
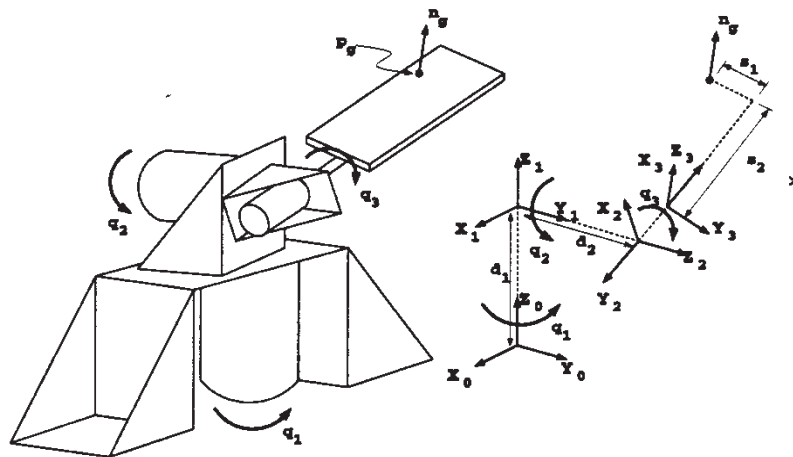
# How is timing done in conventional robotics?

- conventional motion planning: fixed templates of timing encoded in digital computers... determined from trajectory planning algorithms that are purely kinematic, and are realized by servo-controllers that “track” the time plan
- optimal control: planning takes the physical dynamics into account (e.g. optimizing a cost function) .. timing constraints may be added

# How is timing done in autonomous robotics?

## ■ Koditschek's juggling robot:

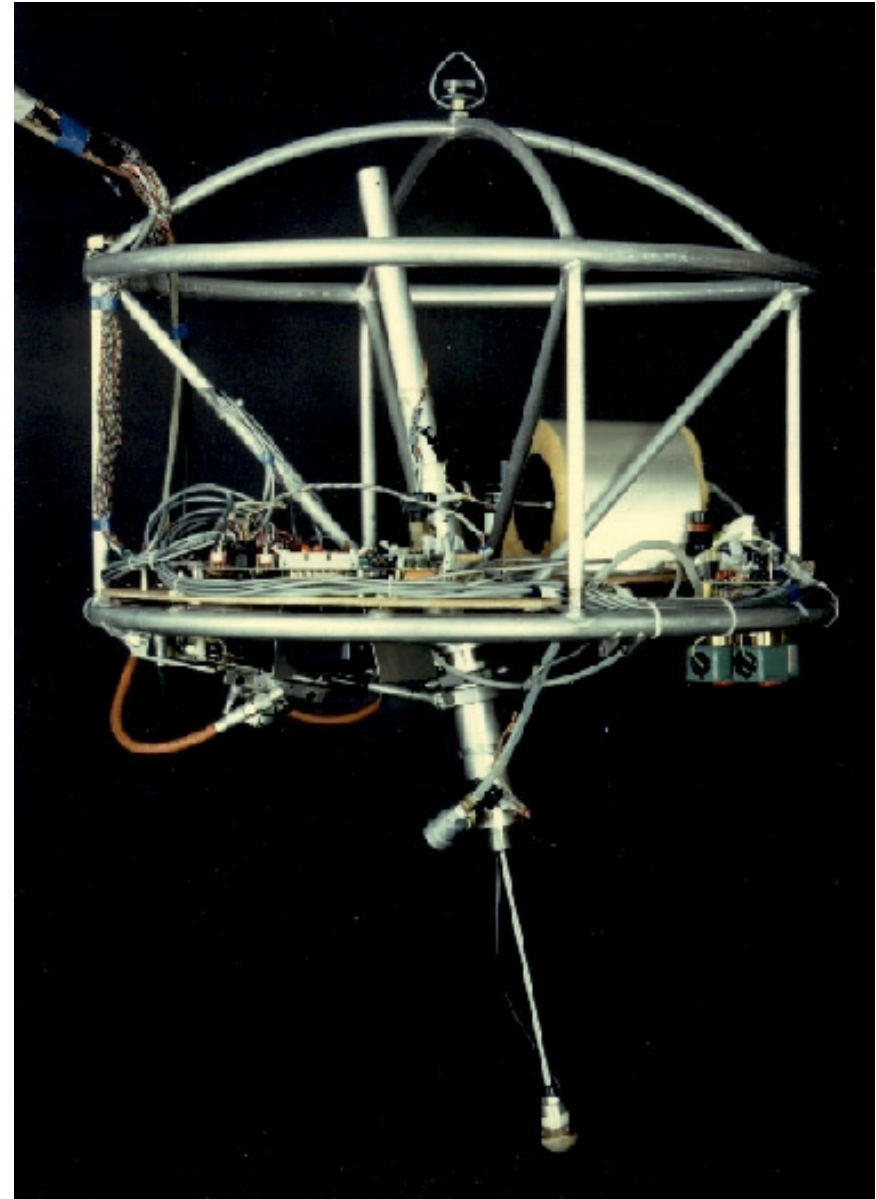
- physical dynamics of bouncing ball modeled... actuator inserts a term into that dynamics so that a periodic solution (limit cycle) results
- ball is kept within reach by conventional P control from contact to contact



# Timing in autonomous robotics

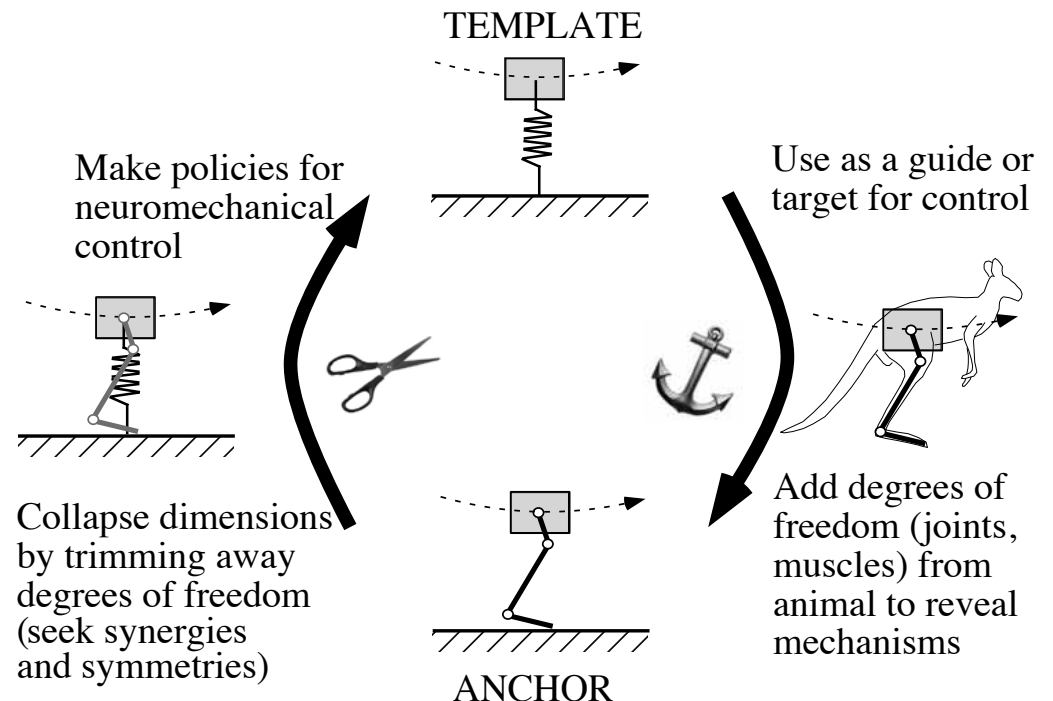
## ■ Raibert's hopping robots

- 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



# Generalize this to bipedal/ quadrupedal locomotion

- template...oscillator at macro-level..
- anchor... kinematics at joint/actuator level



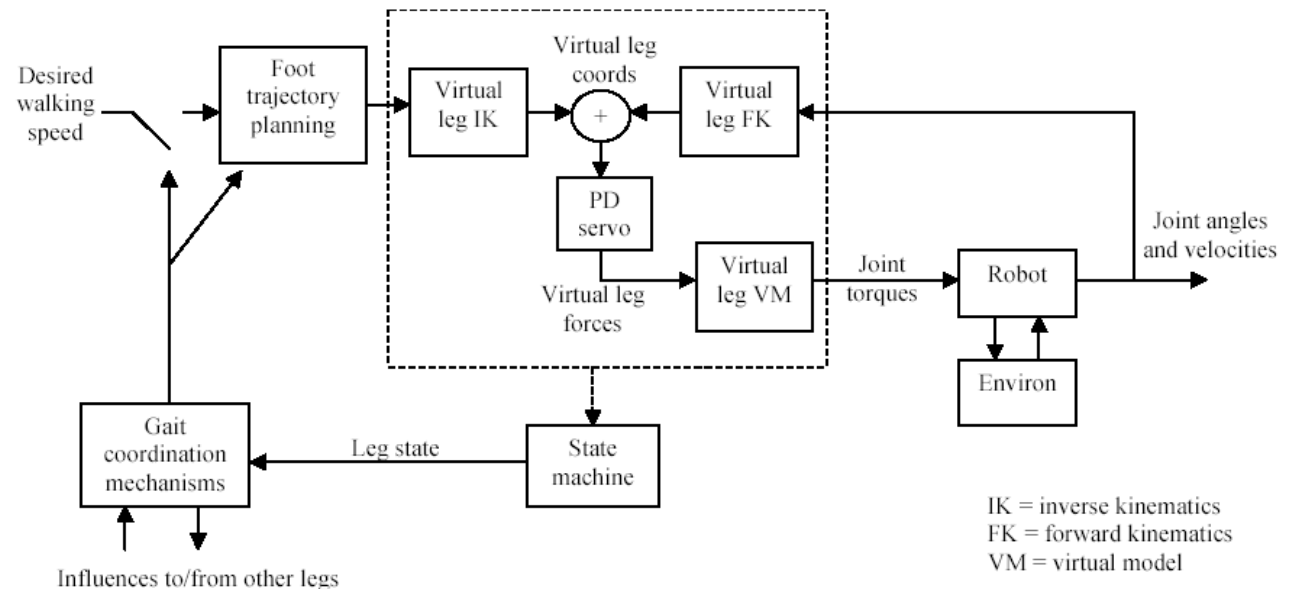
[Full Koditschek 99]

# How is timing done in autonomous robotics?

## ■ Raibert's bio-dog

■ expand that idea to coordination among limbs

■ => technical variant

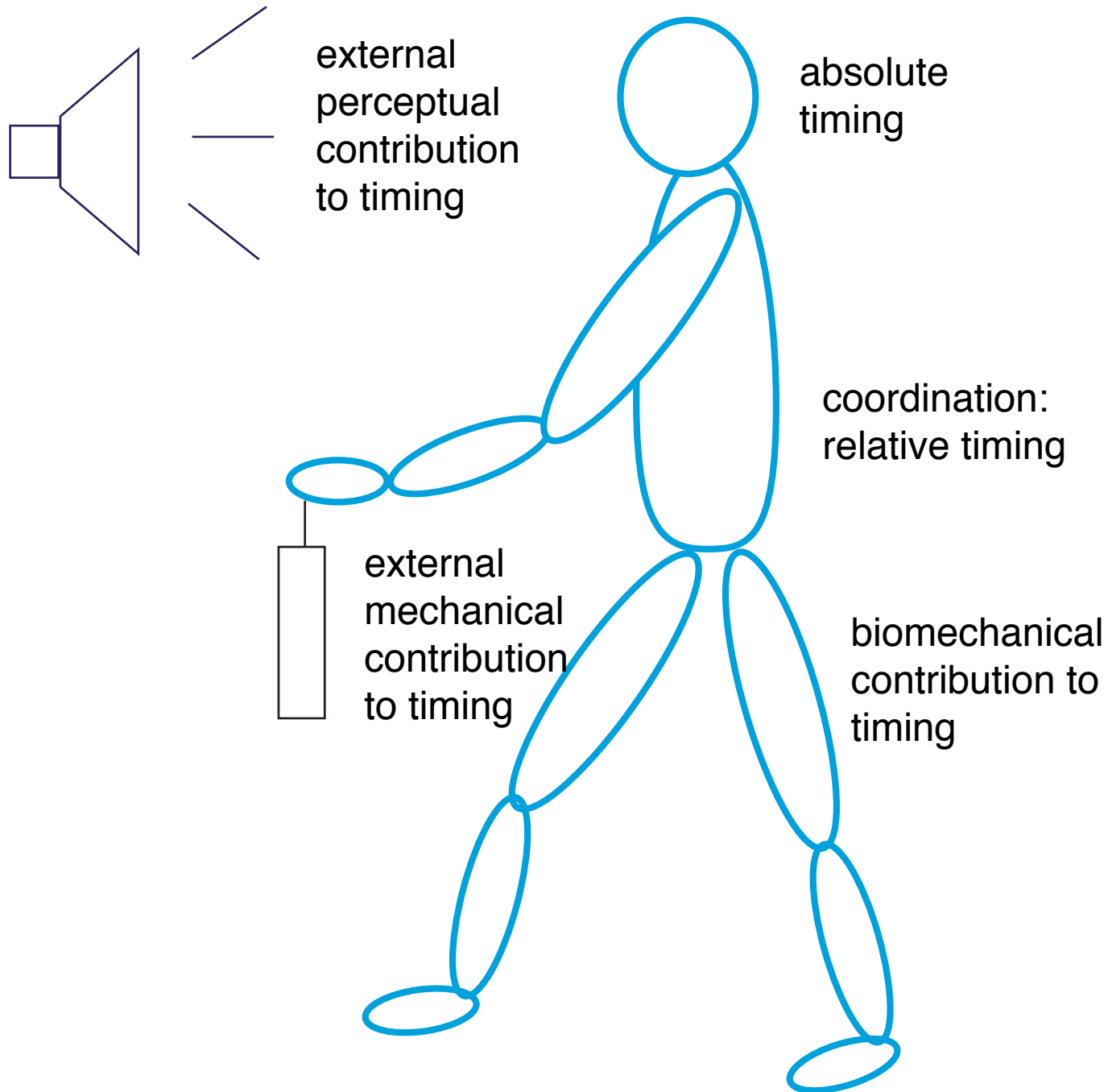




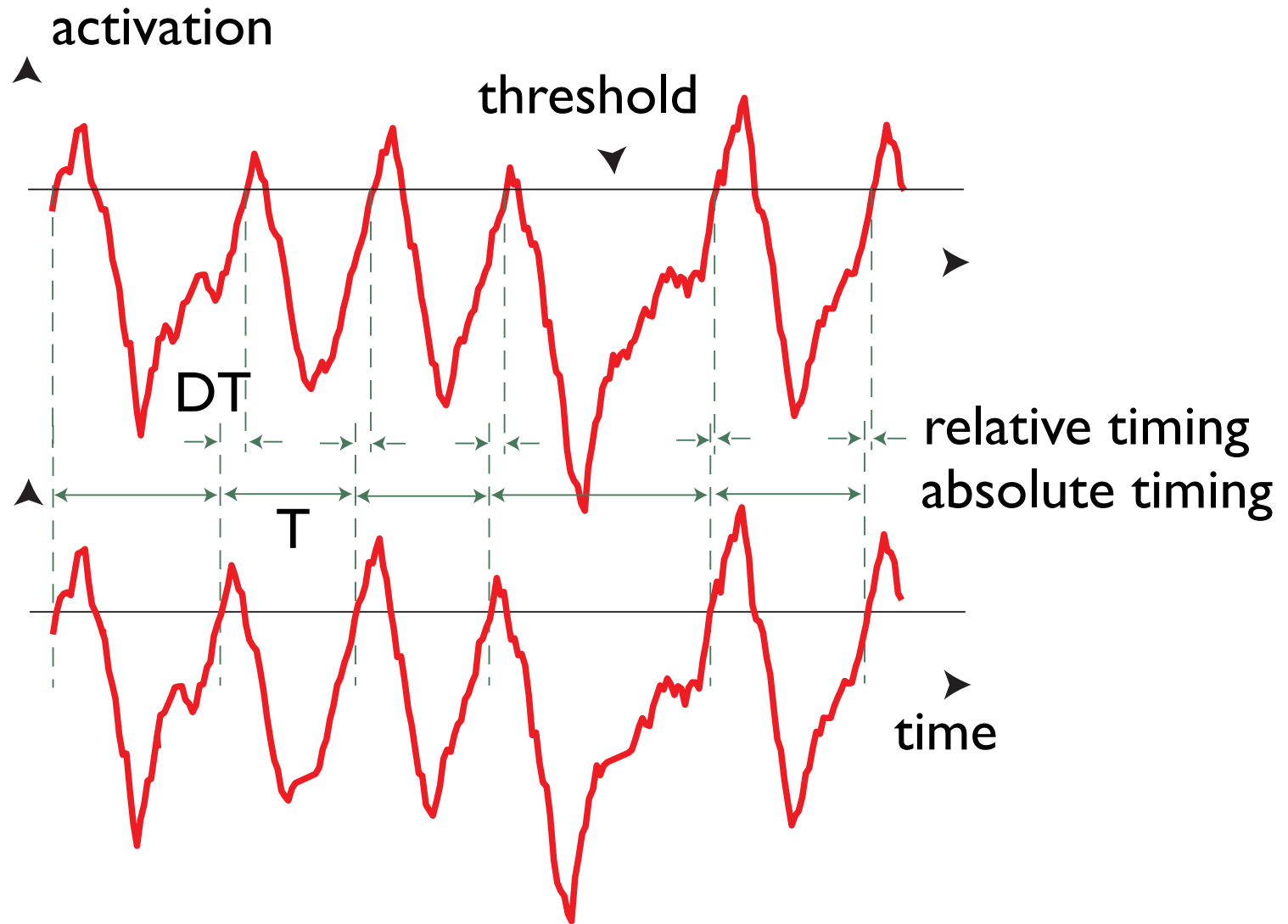
# How is timing done in autonomous robotics?

[https://www.youtube.com/  
watch?v=M8YjvHYbZ9w](https://www.youtube.com/watch?v=M8YjvHYbZ9w)

# Timing in nervous systems



# Relative vs. absolute timing



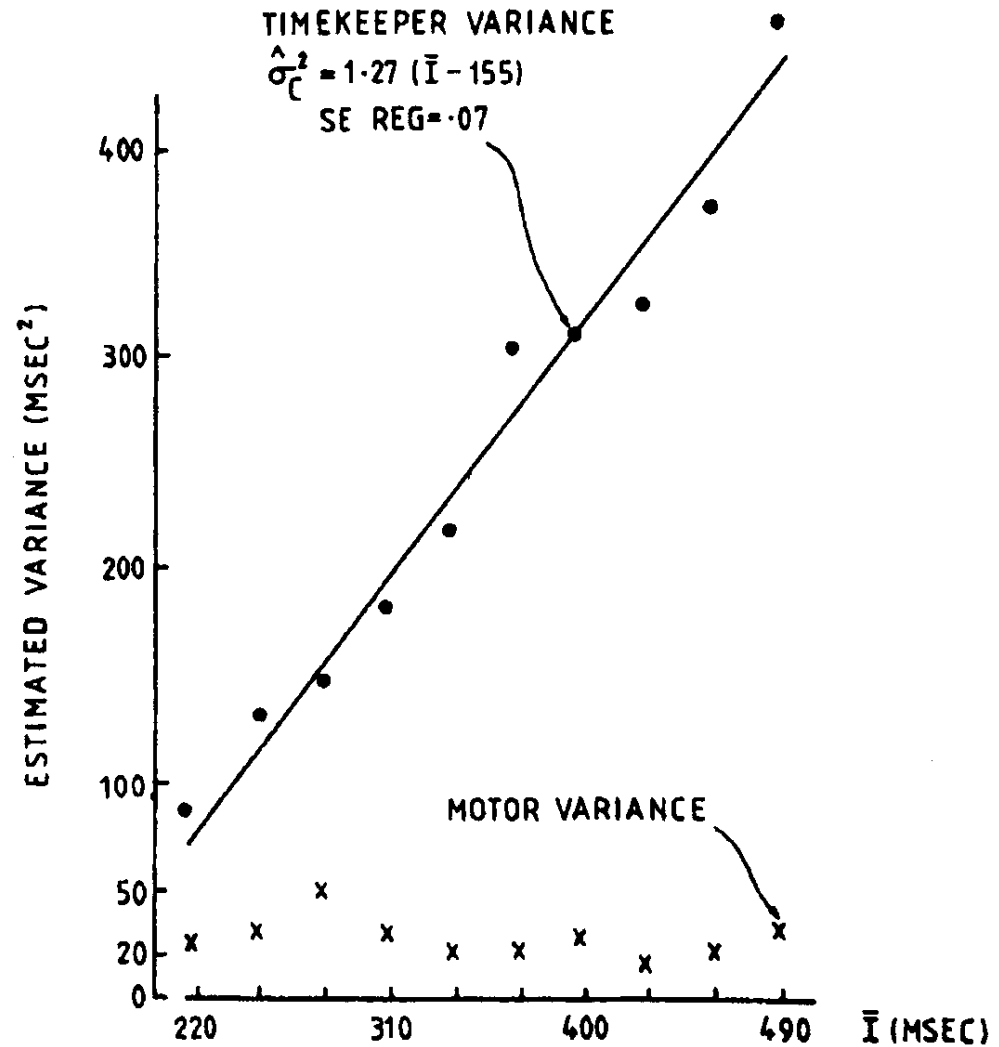
$$\text{relative phase} = DT/T$$

# 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

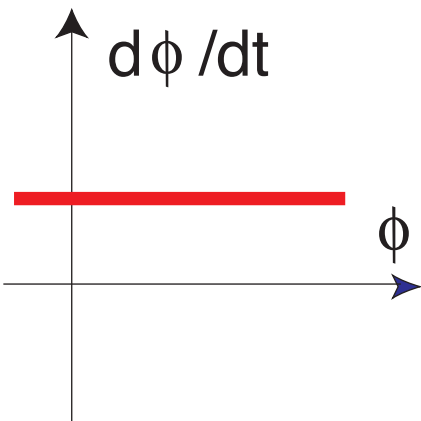
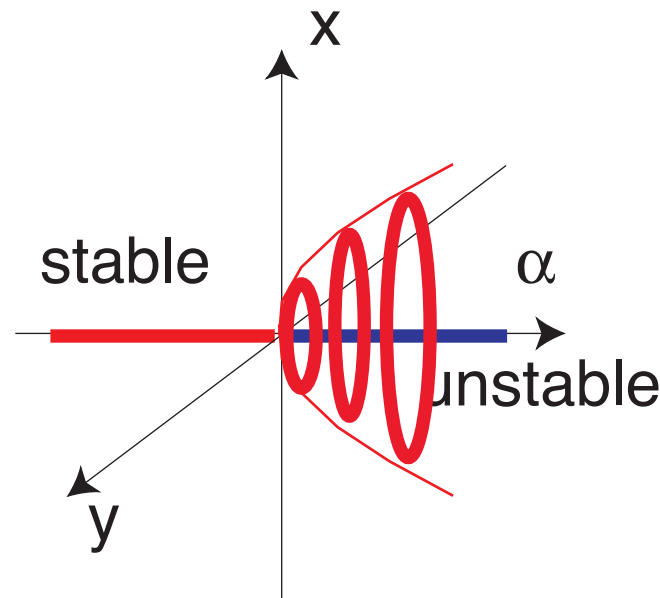
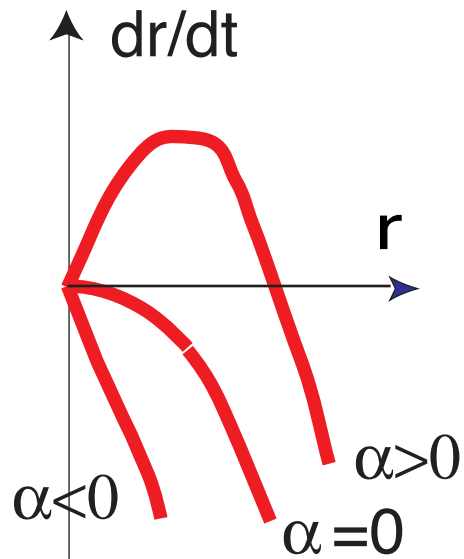
$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} \alpha & -\omega \\ \omega & \alpha \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} - (x^2 + y^2) \begin{pmatrix} x \\ y \end{pmatrix}$$

$$x = r \cos(\phi)$$

$$\dot{r} = \alpha r - r^3$$

$$y = r \sin(\phi)$$

$$\dot{\phi} = \omega$$



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

amplitude  $A = \sqrt{\alpha}$

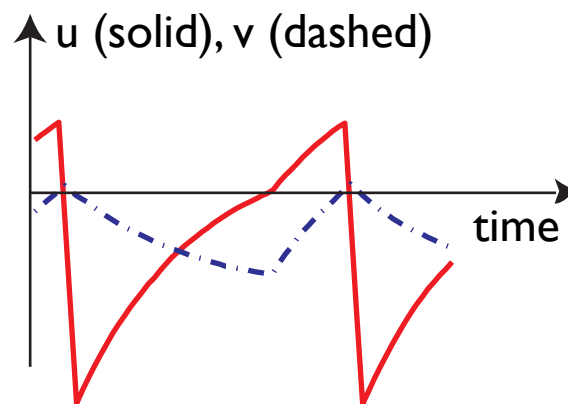
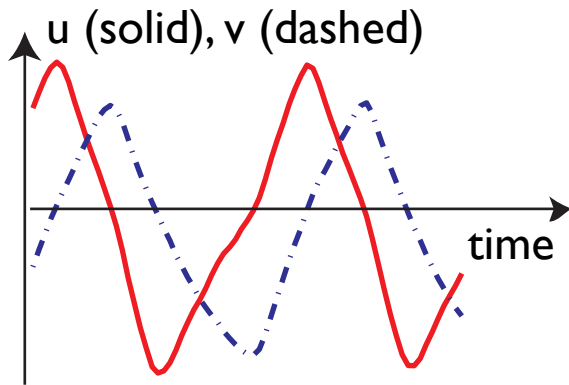
cycle time  $T = 2\pi/\omega$ ,

# Neural oscillator

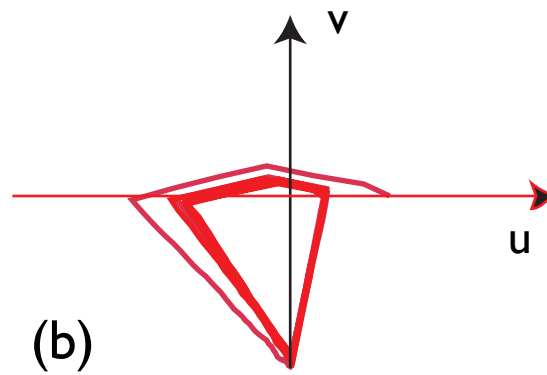
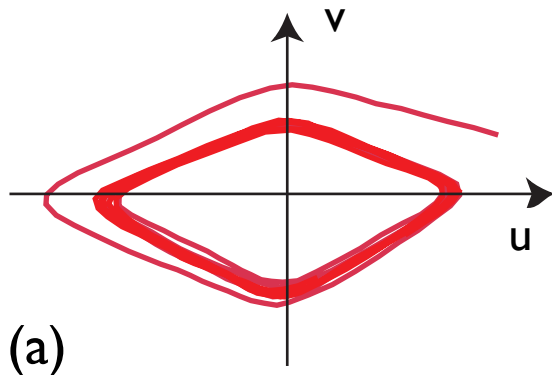
■ relaxation oscillator

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

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

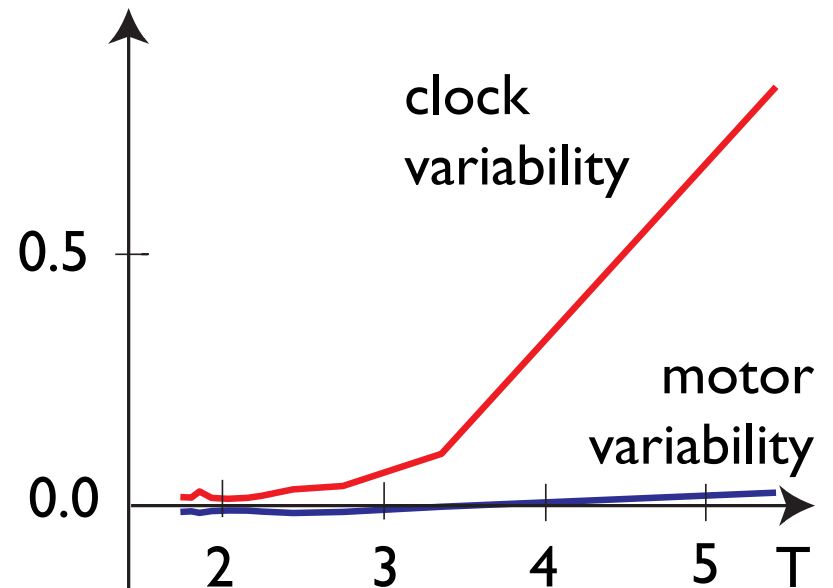
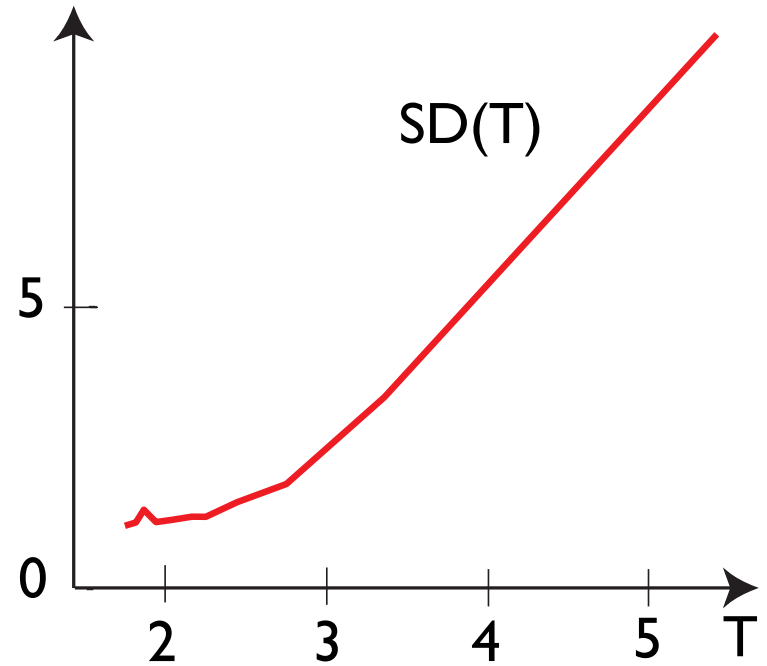


[Amari 77]





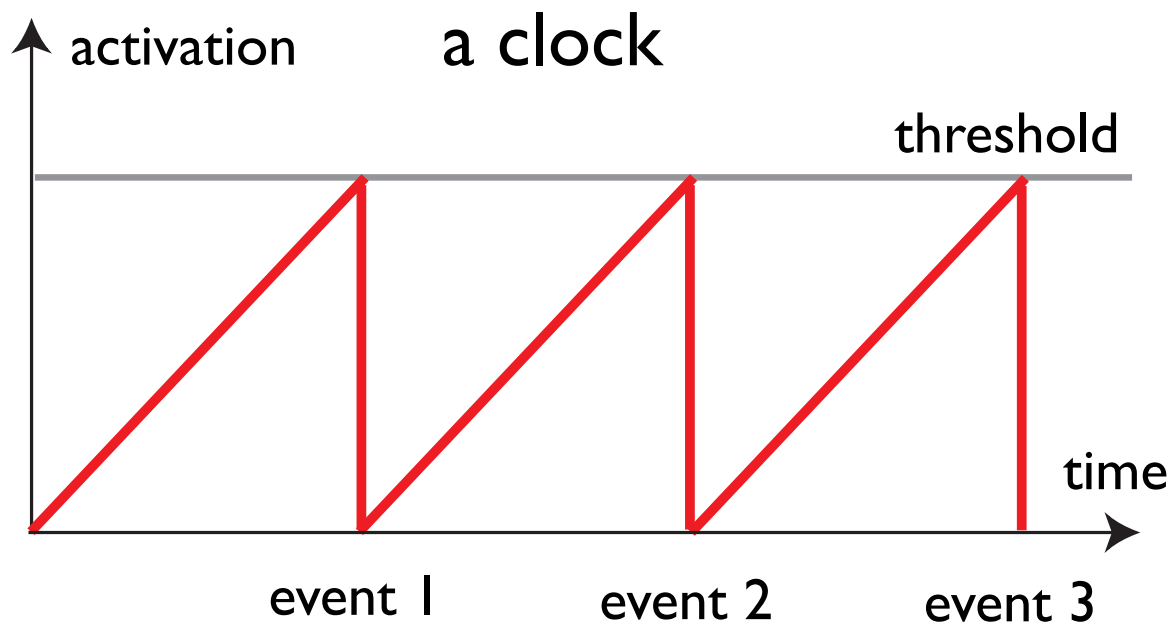
# Neural oscillator accounts for variance of absolute timing



[Schöner 2002]

# Clocks

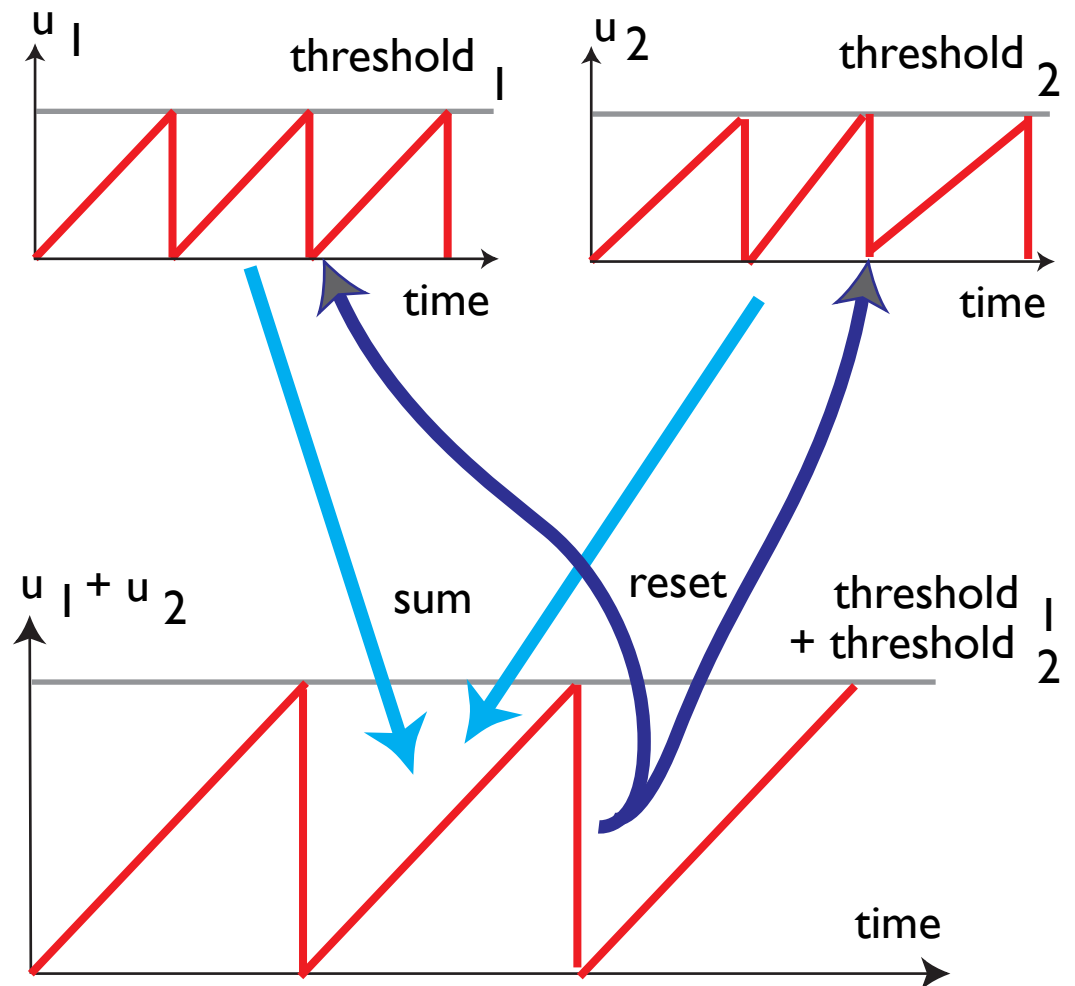
- hour glasses are also oscillators
- but: it is critical to include the “resetting”



[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

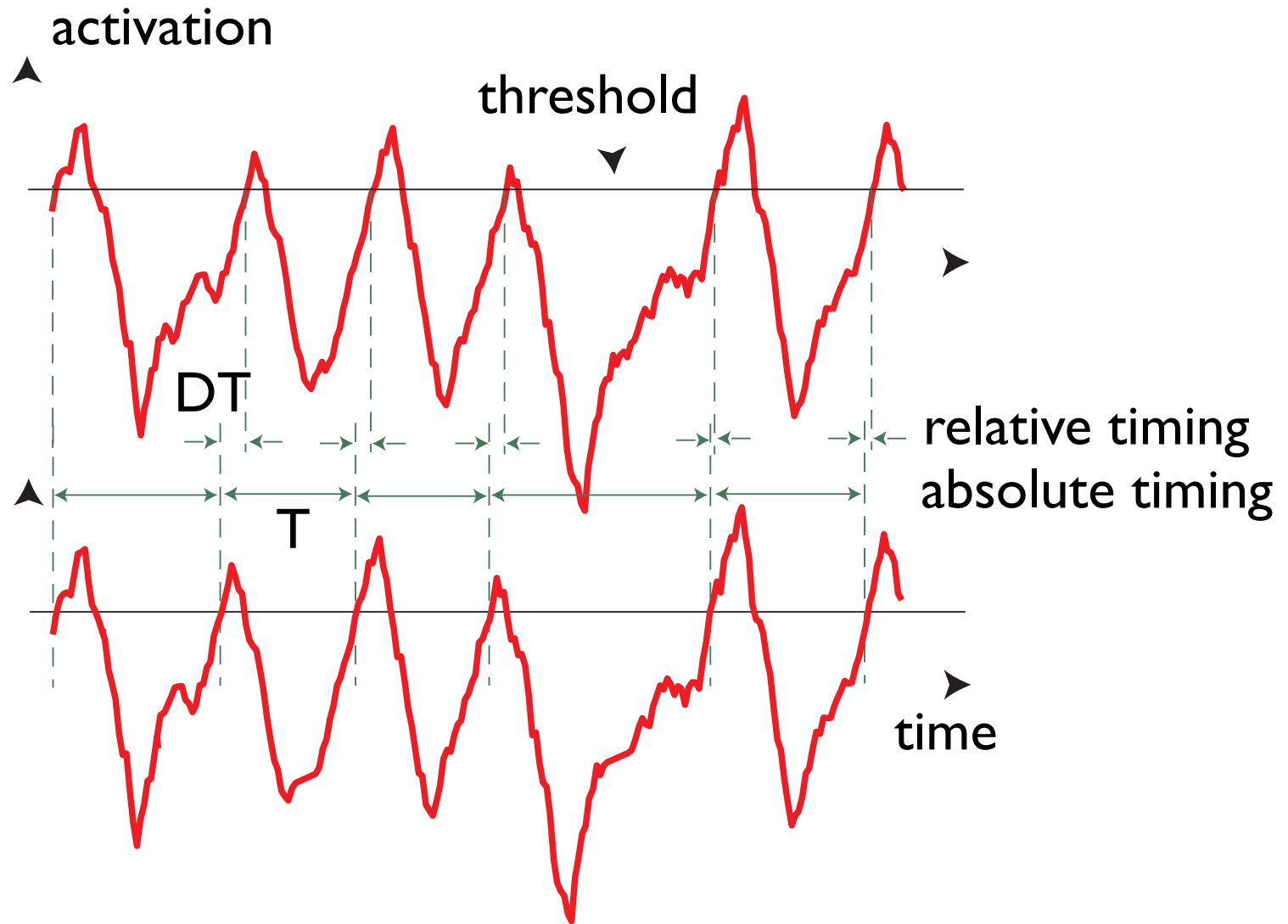
# Definition of coordination

- 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)

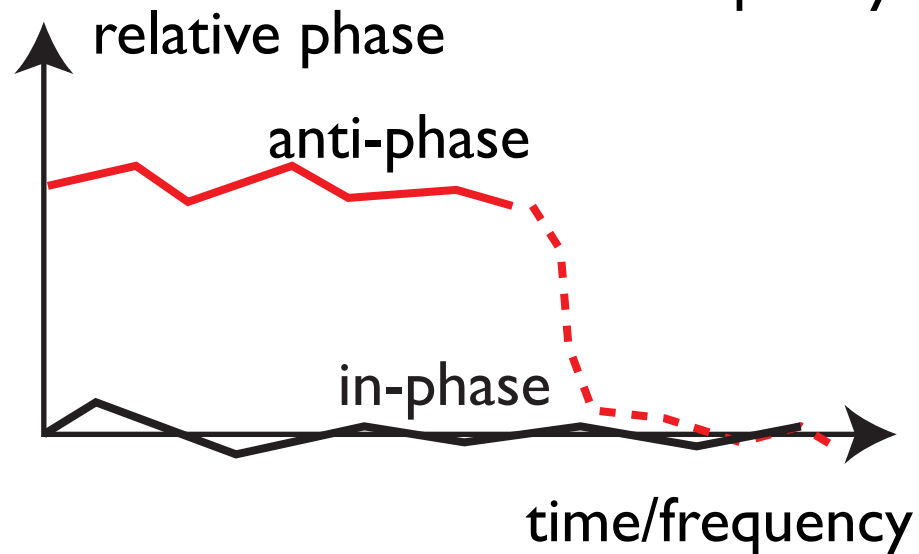
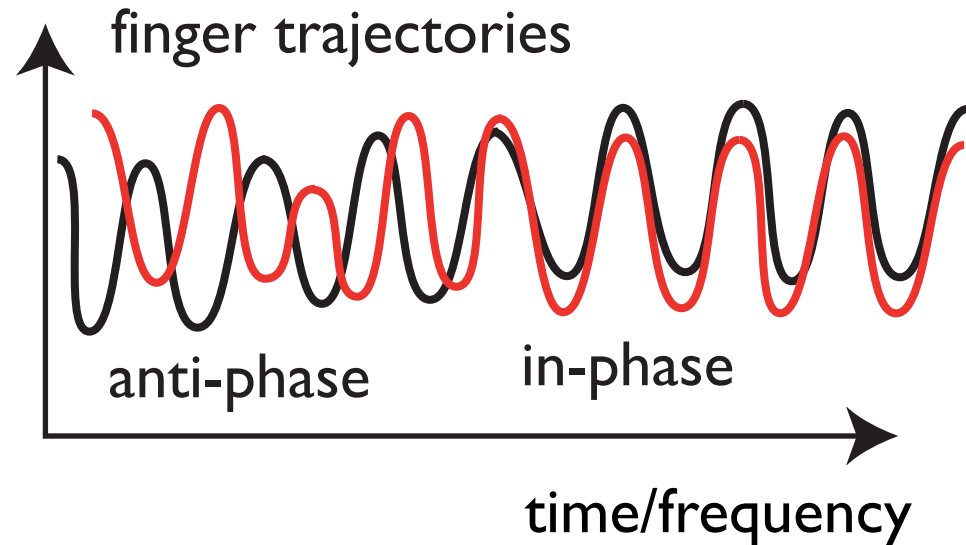
## ■ anti-phase or phase alternation

- syncopation

- e.g., trot

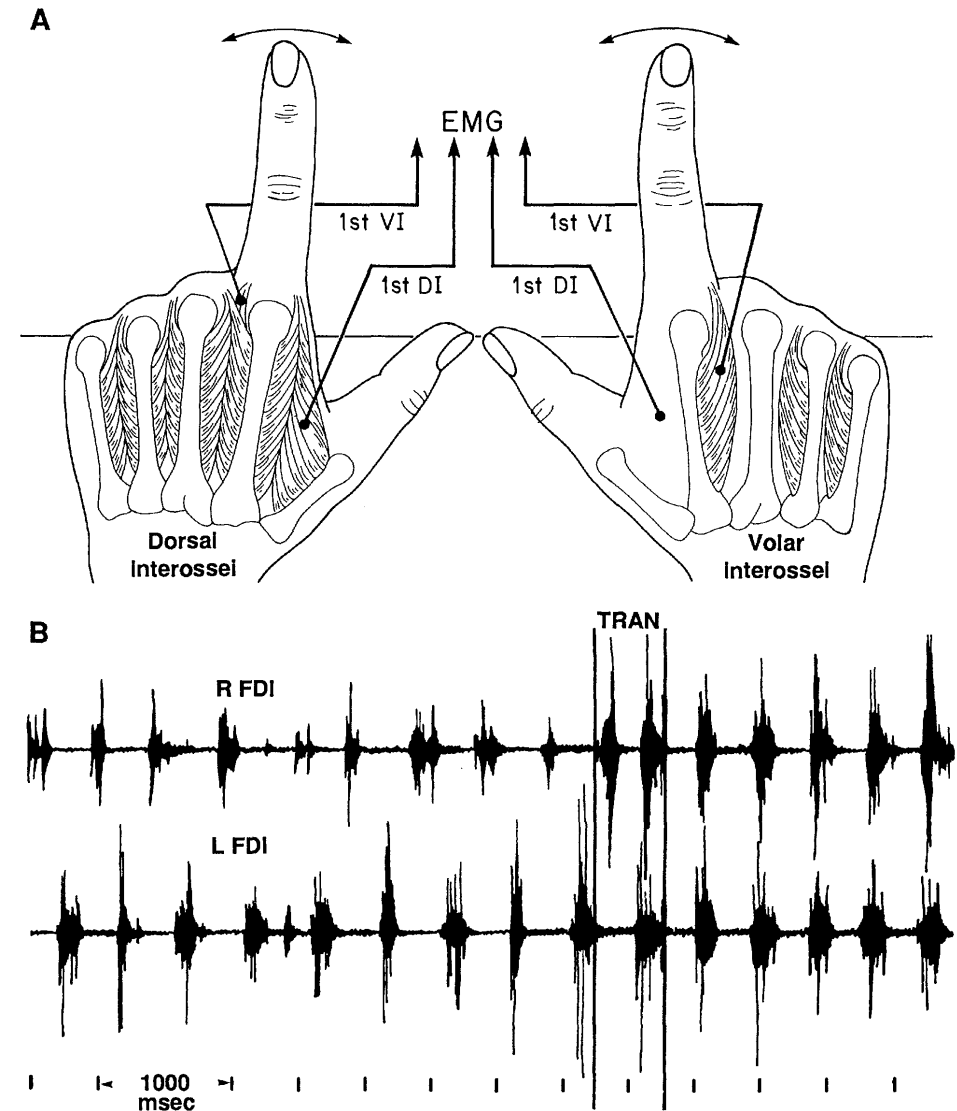
# An instability in rhythmic movement coordination

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



# Instability

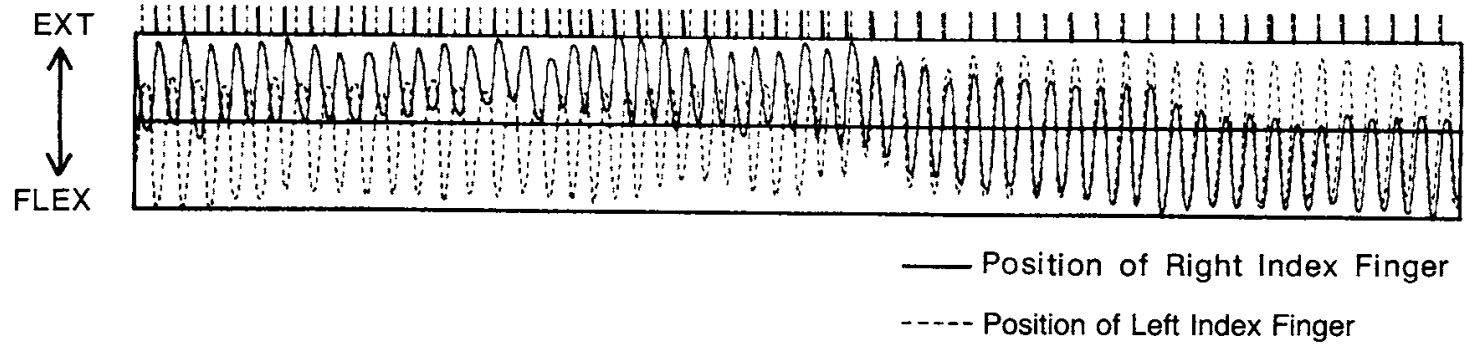
- experiment involves finger movement
- why fingers?
  - no mechanical coupling
  - constraint of maximal frequency irrelevant
  - => pure neurally based coordination



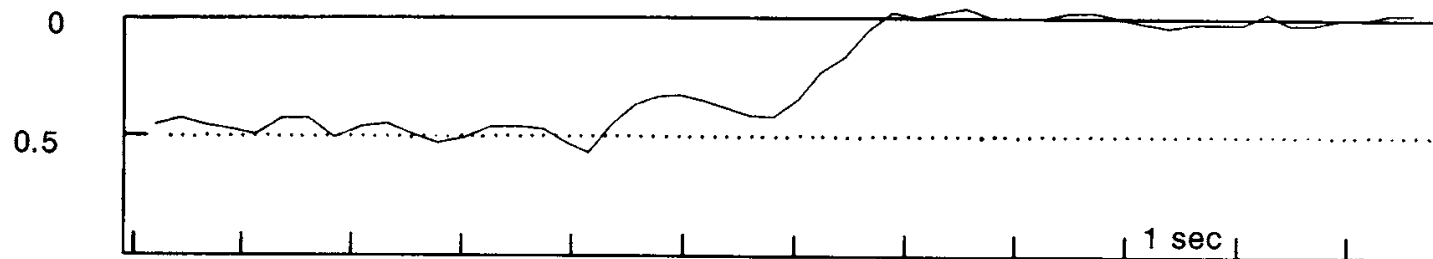
# Instability

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

### A. TIME SERIES



### B. CYCLE ESTIMATE OF RELATIVE PHASE

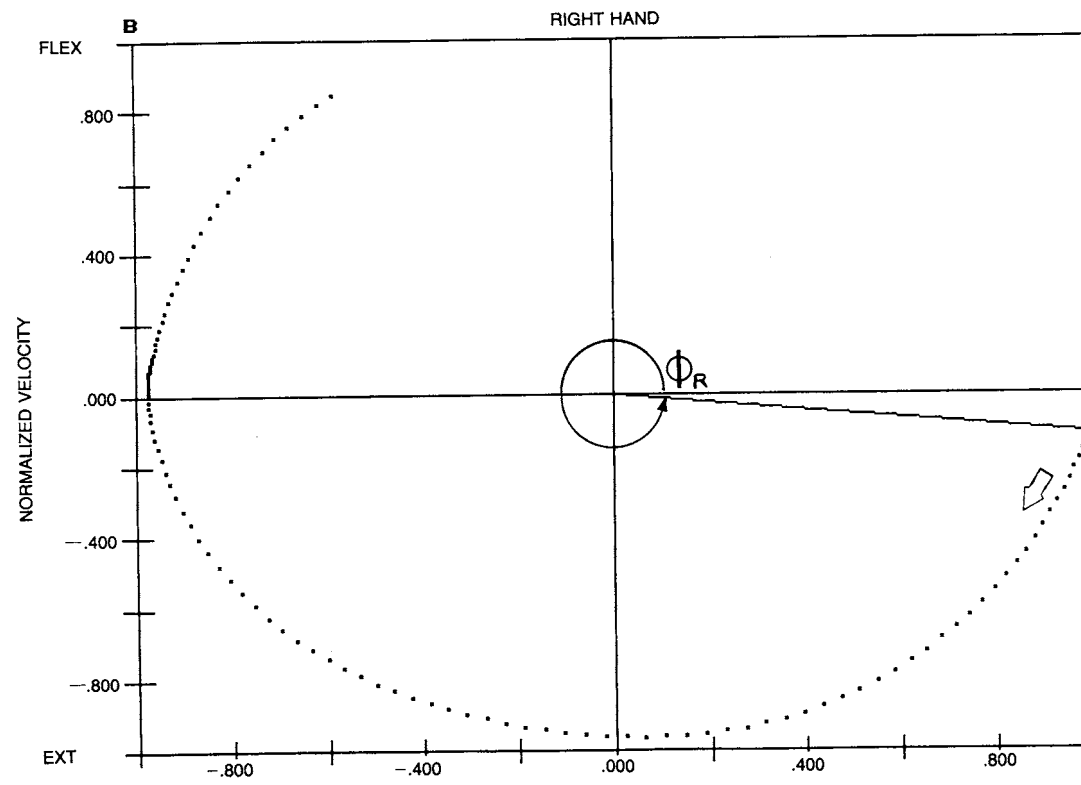
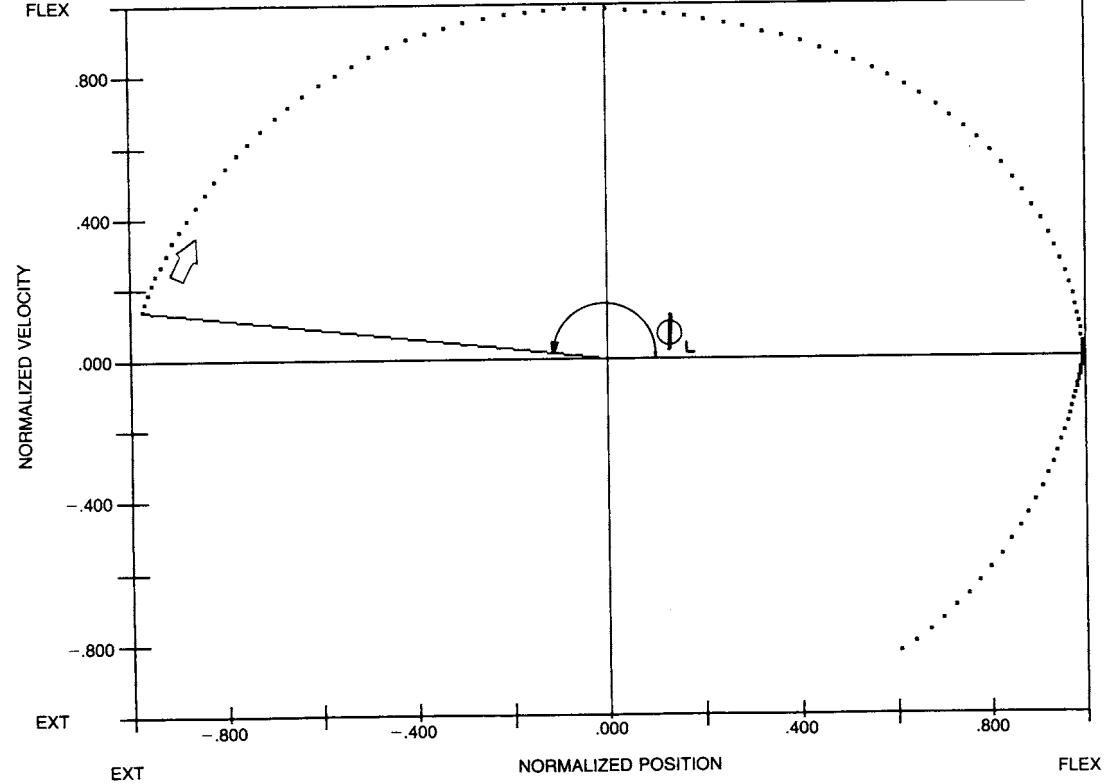


### C. INDIVIDUAL SAMPLE ESTIMATE OF RELATIVE PHASE



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

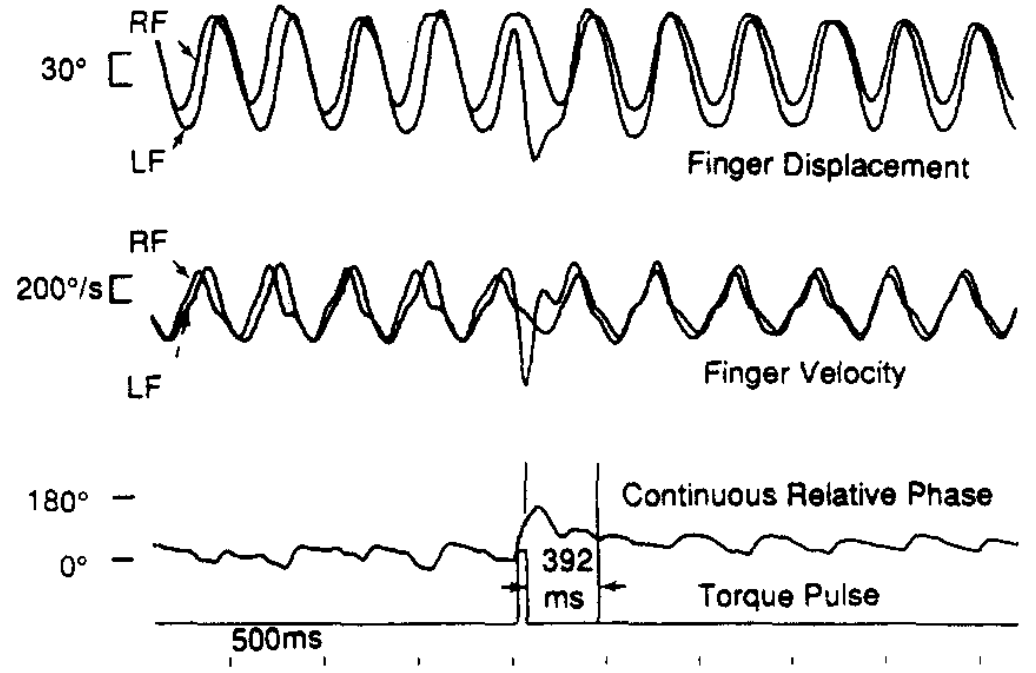
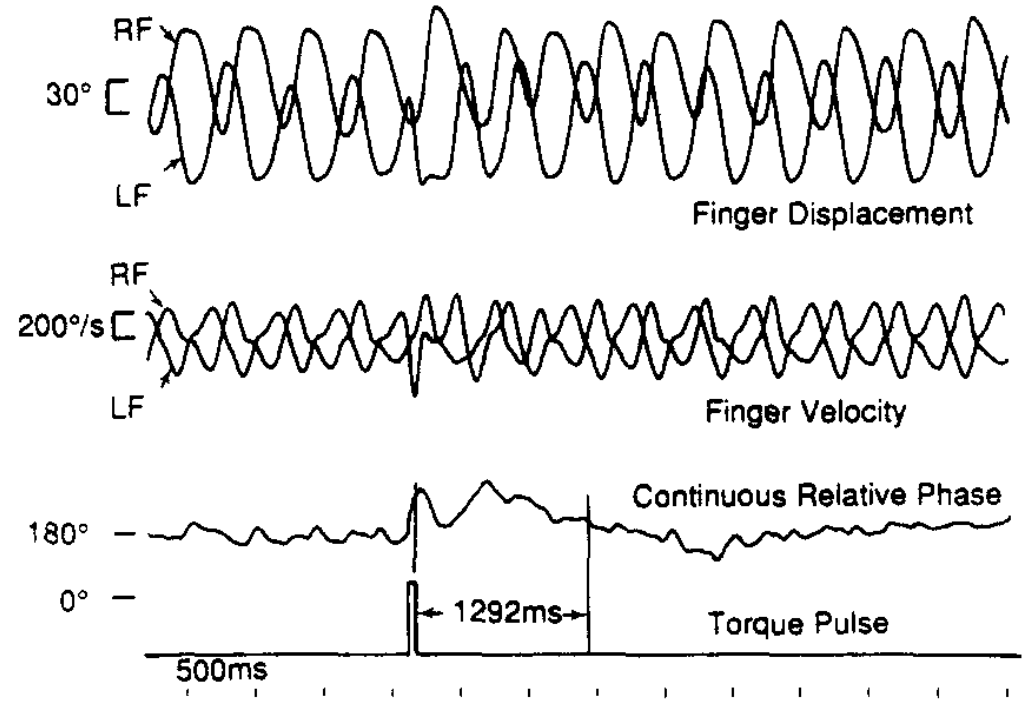
## ■ relaxation time

- 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

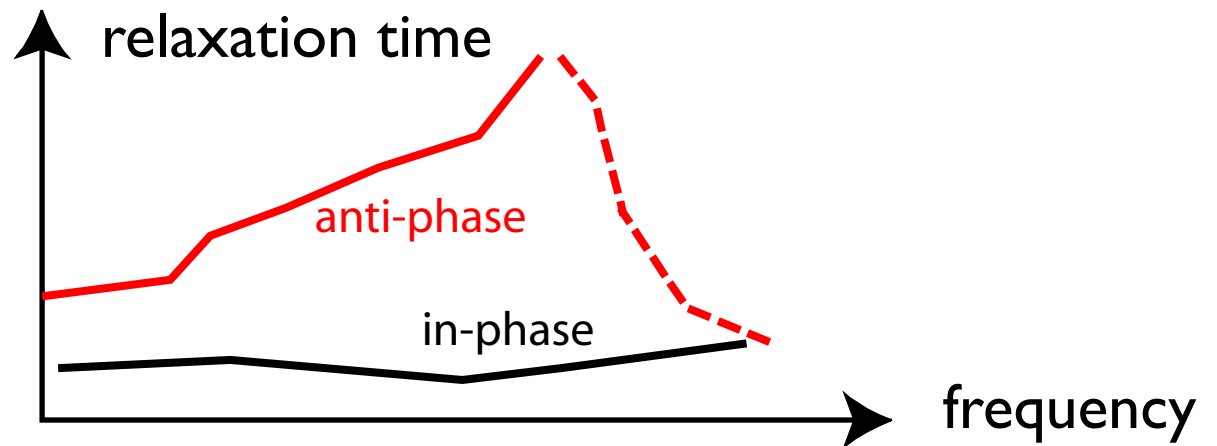
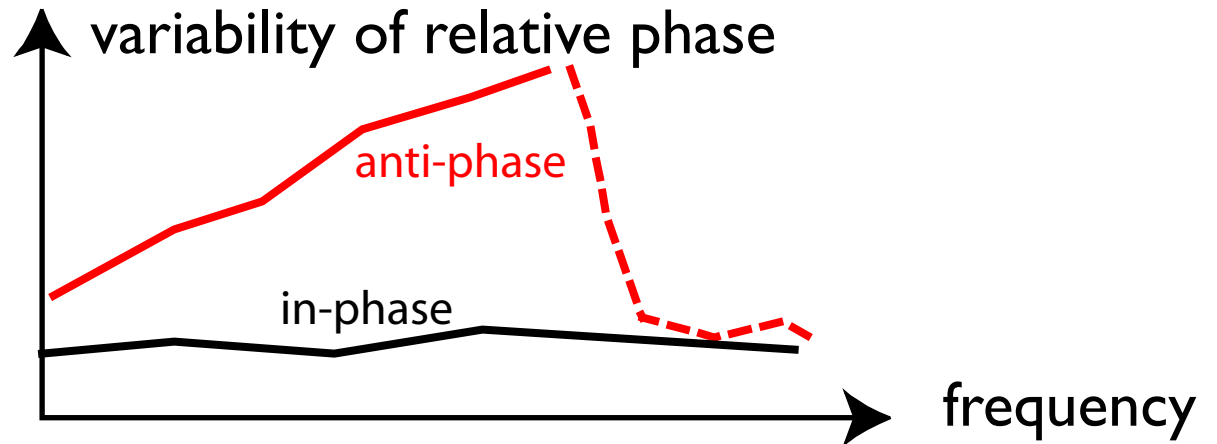
- the less stable, the longer relaxation time

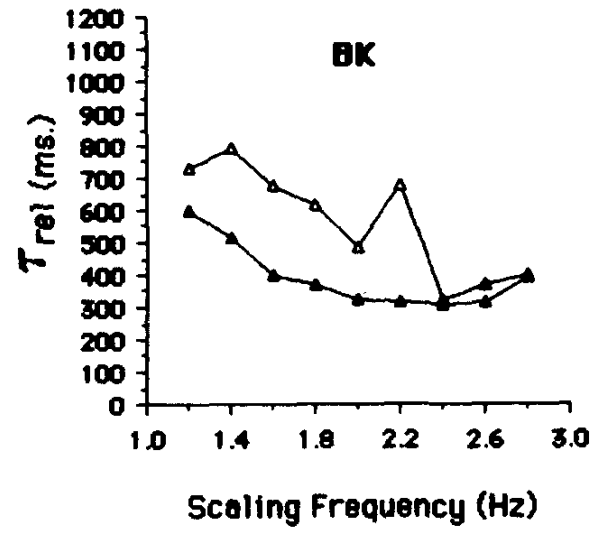
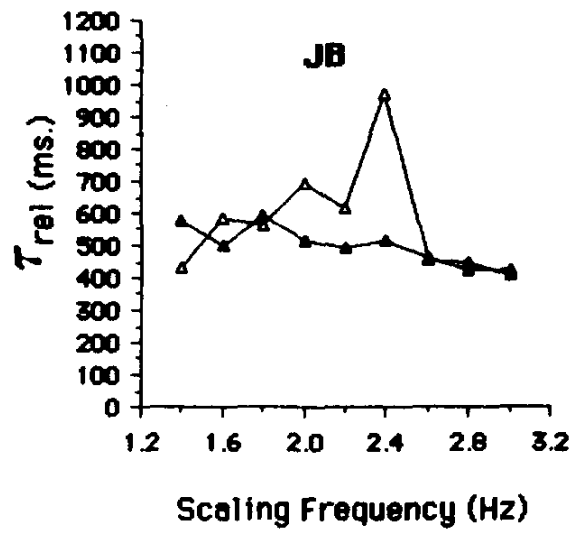
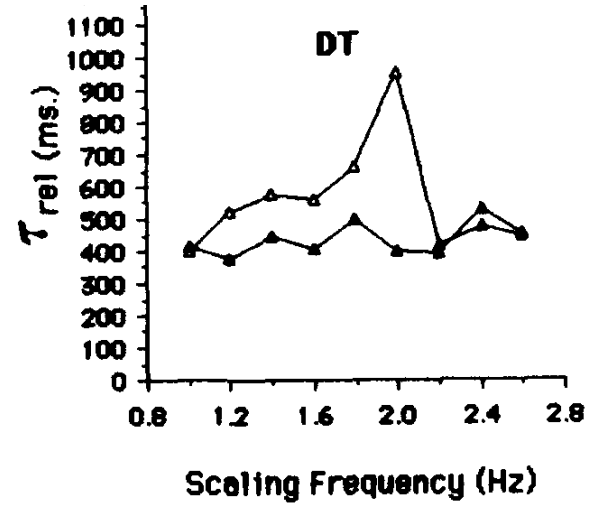
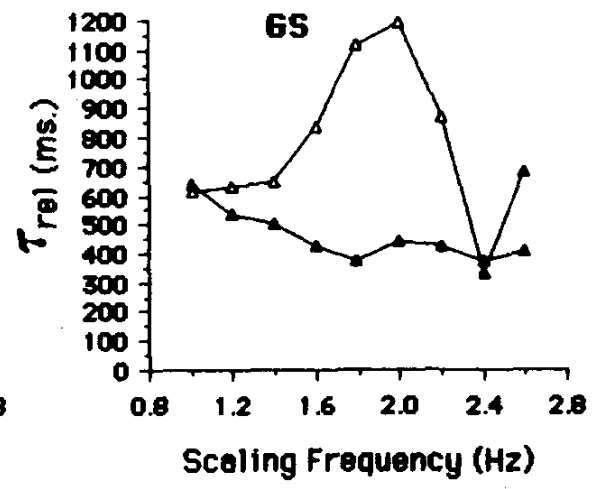
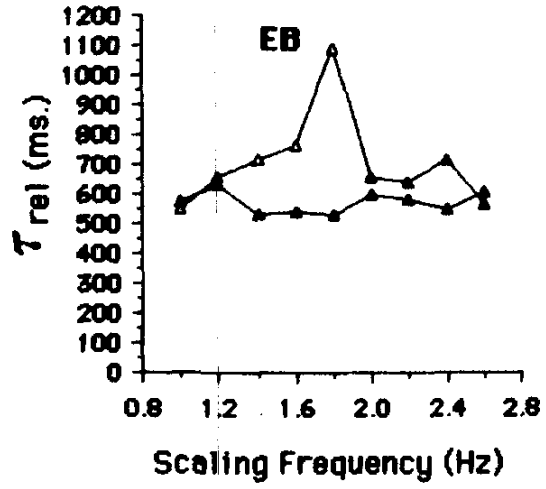
data example  
perturbation of  
fingers and  
relative phase



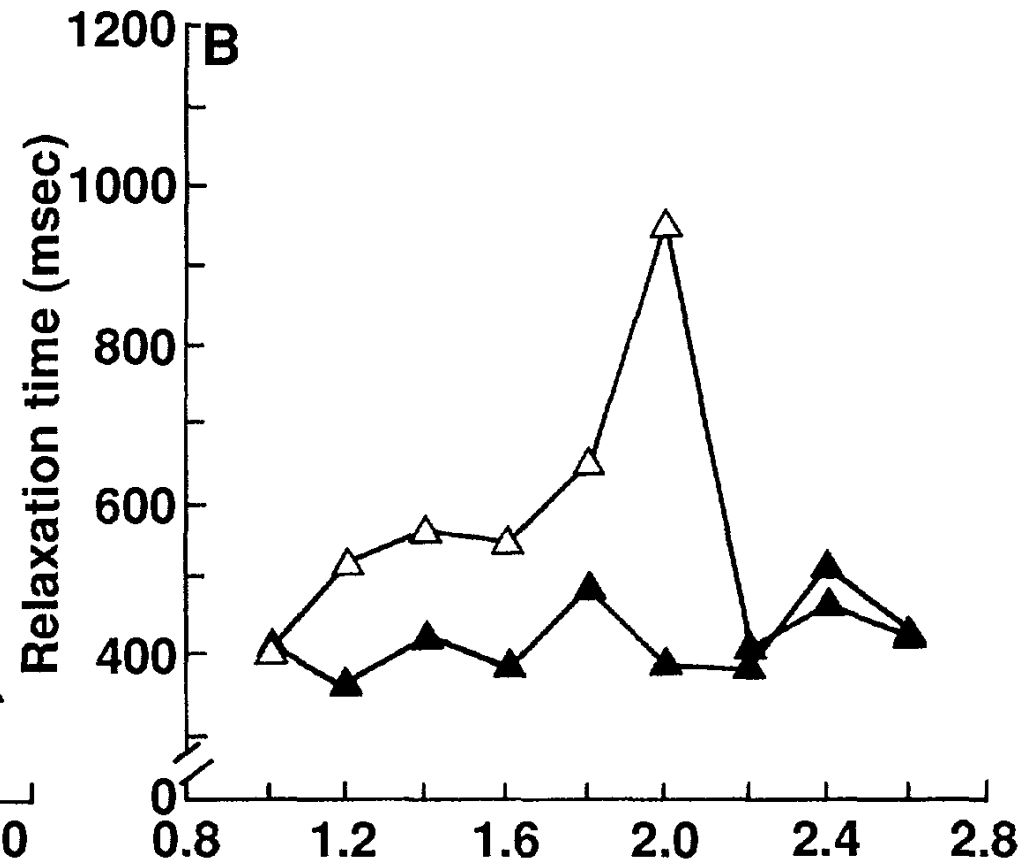
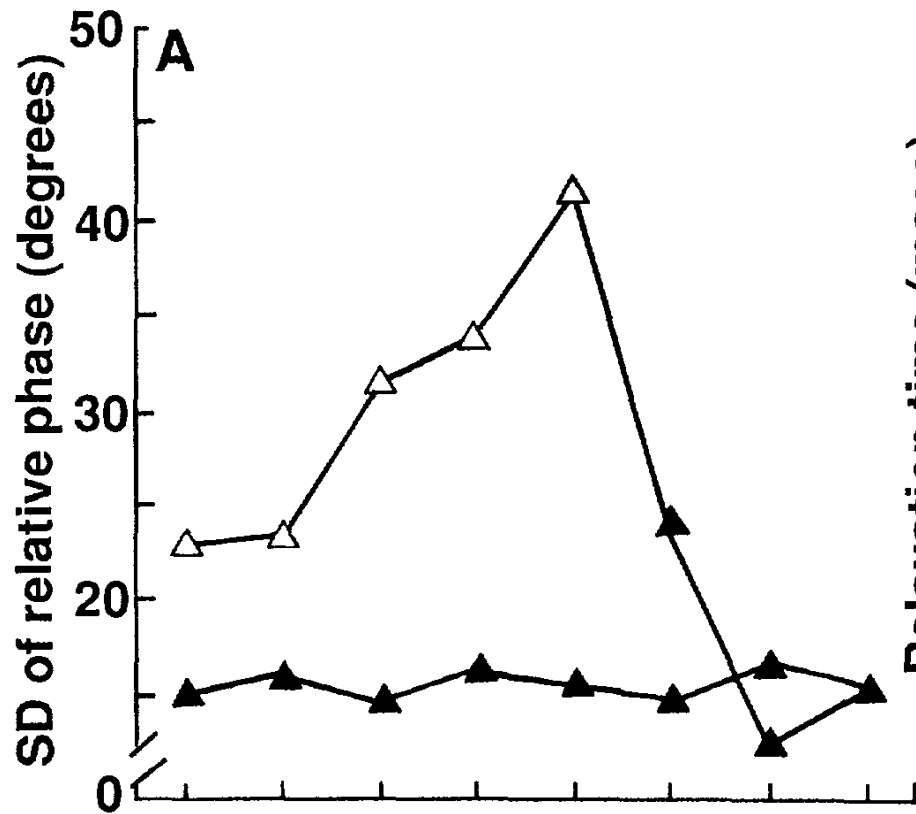
# Signatures of instability

- loss of stability indexed by measures of stability





relaxation times, individual data



Frequency (Hz)

data (averaged across subjects)

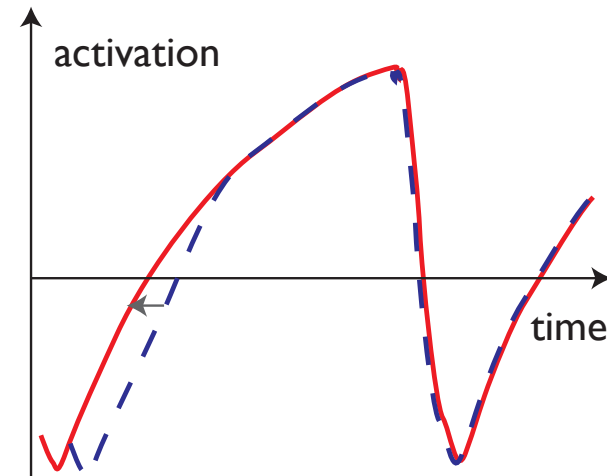
Schöner, Kelso (Science, 1988)

# 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



$$\tau \dot{u}_1 = -u_1 + h_u + w_{uu}f(u_1) - w_{uv}f(v_1)$$

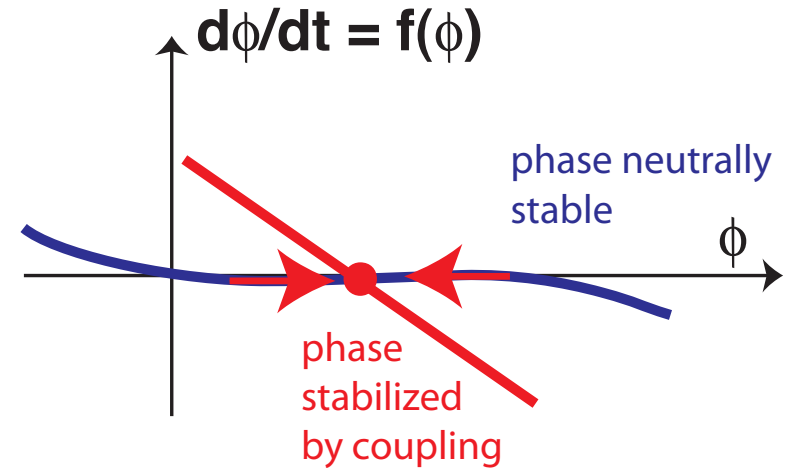
$$\tau \dot{v}_1 = -v_1 + h_v + w_{vu}f(u_1) + cf(u_2)$$

$$\tau \dot{u}_2 = -u_2 + h_u + w_{uu}f(u_2) - w_{uv}f(v_2)$$

$$\tau \dot{v}_2 = -v_2 + h_v + w_{vu}f(u_2) + cf(u_1)$$

# Movement timing

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



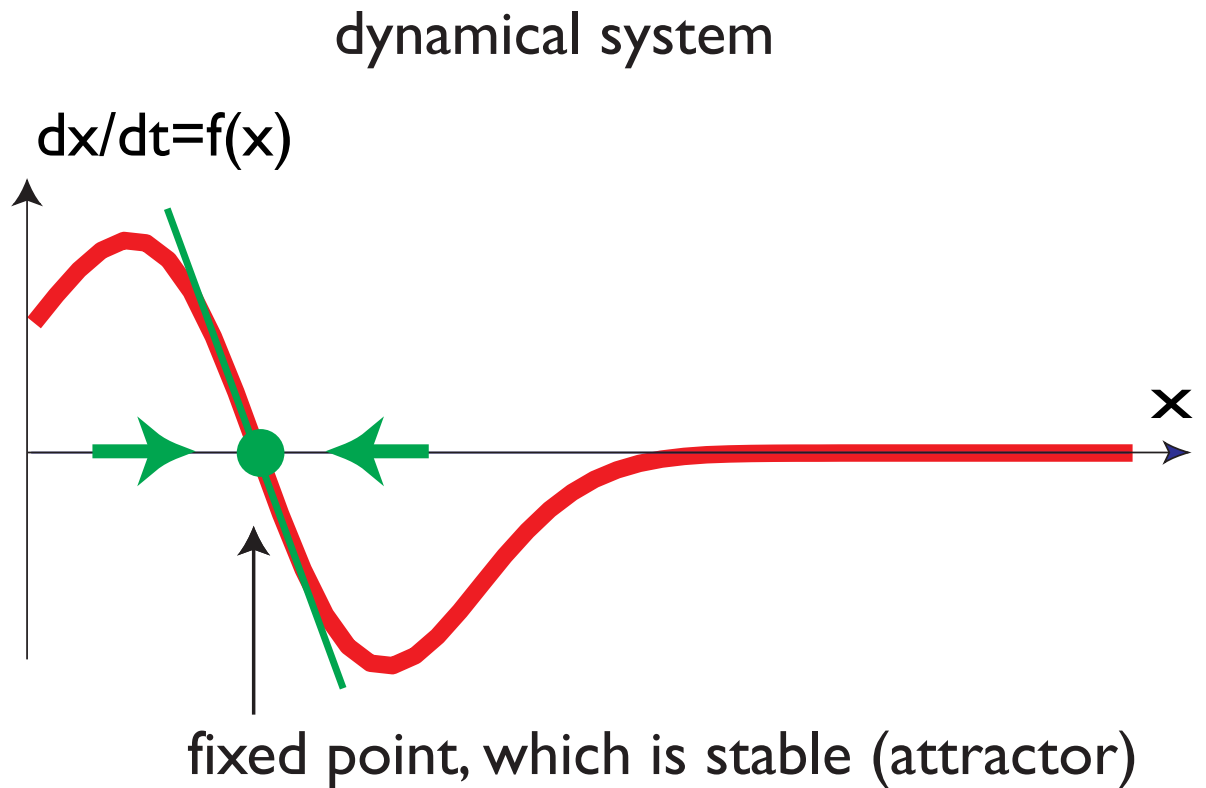


# Dynamical systems account of instability

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

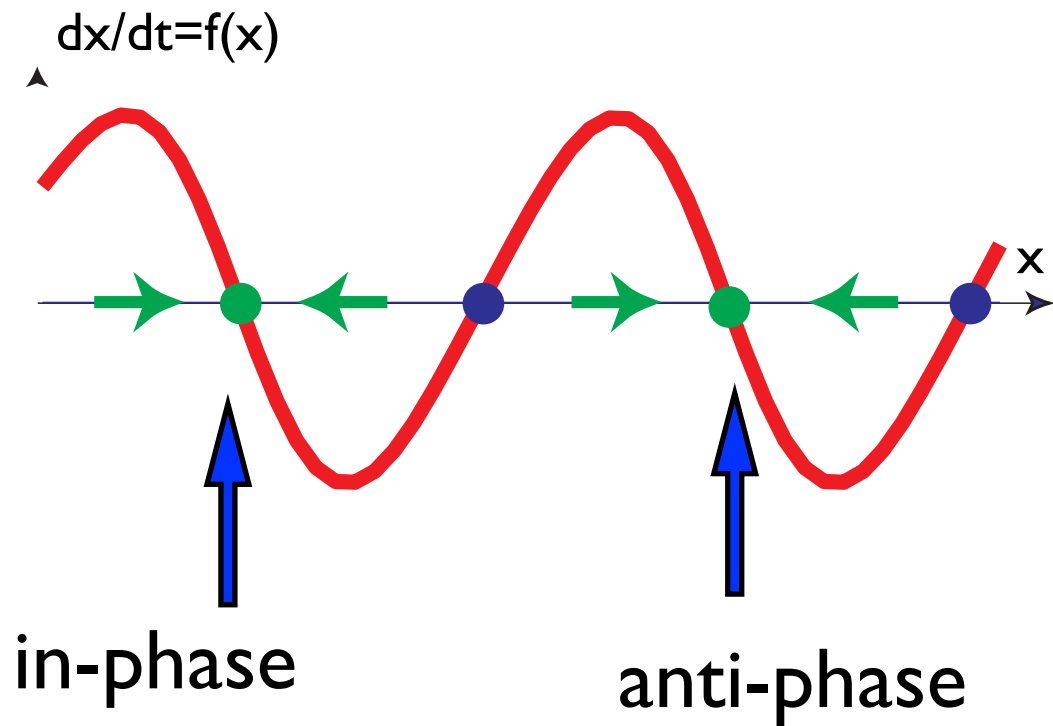
# Dynamical systems account of instability

- state of dynamical system  $x$  = relative phase



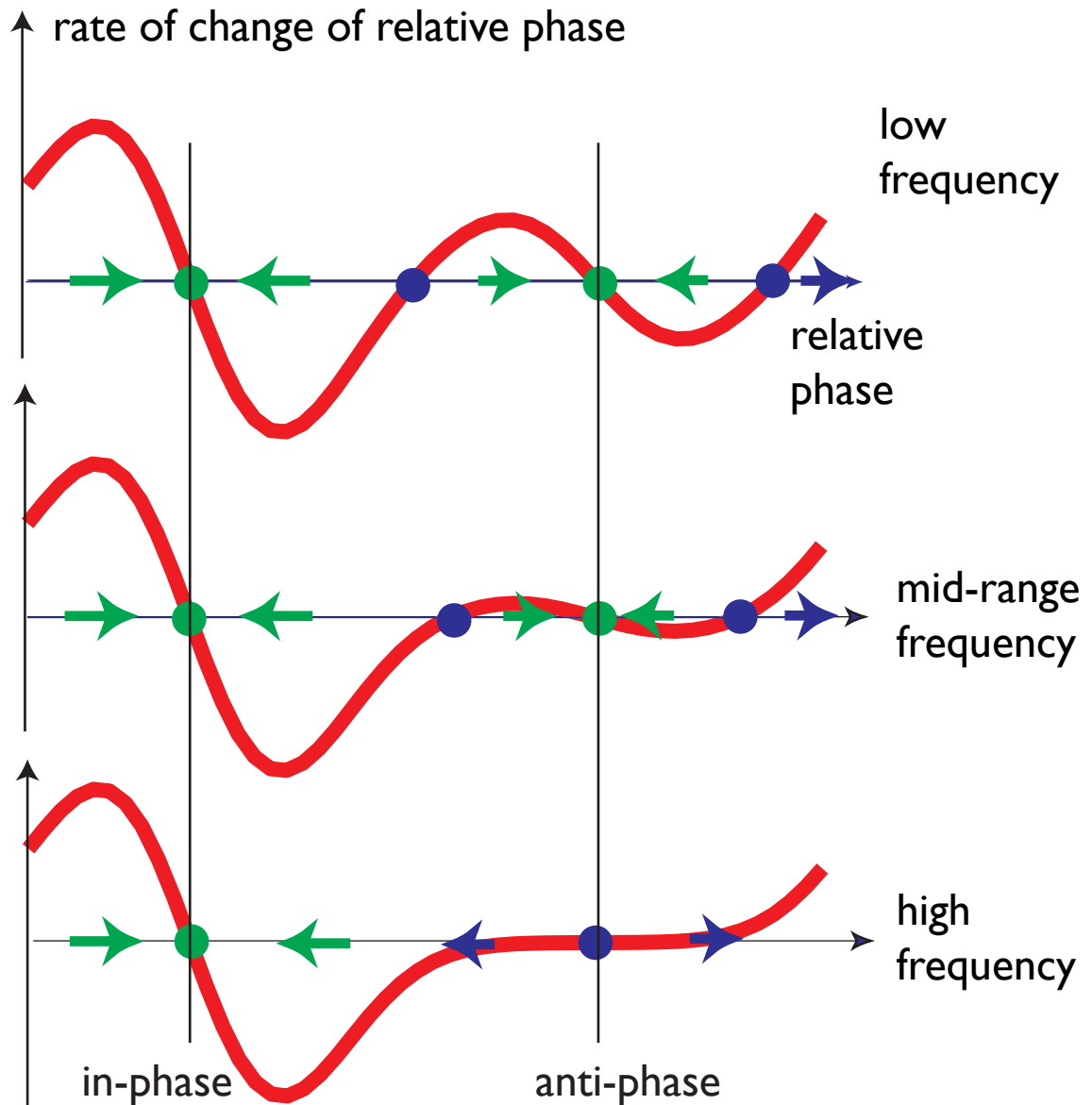
# Dynamical systems account of instability

- at low frequencies this system is bistable

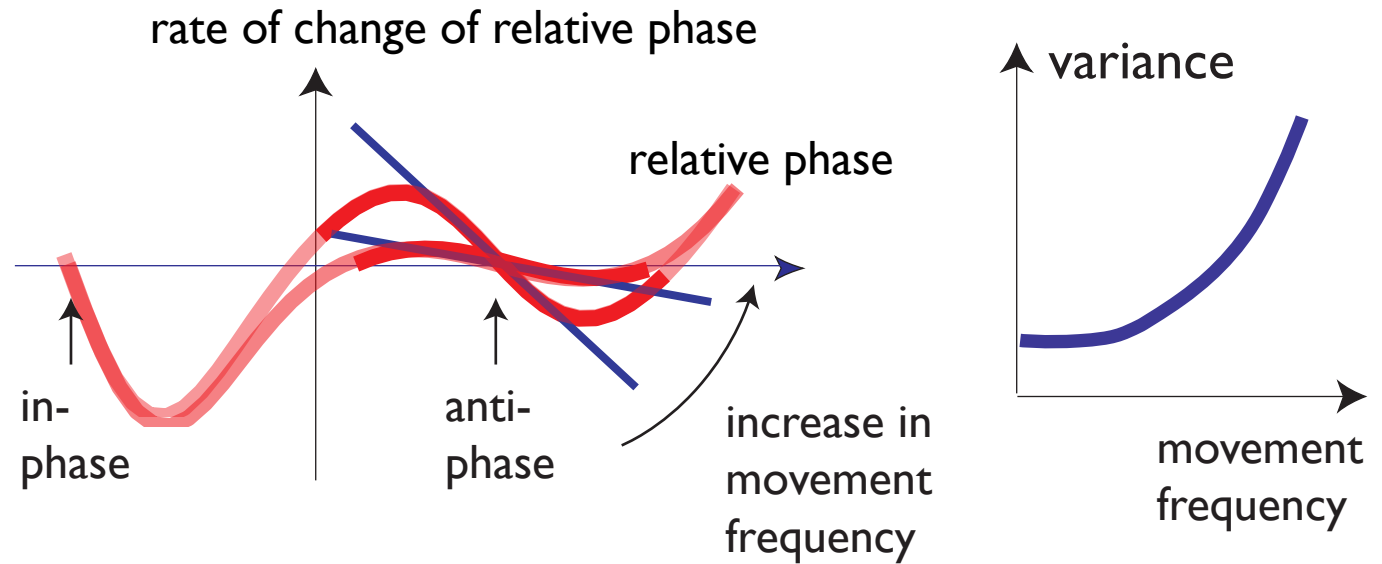


# Dynamical systems account of instability

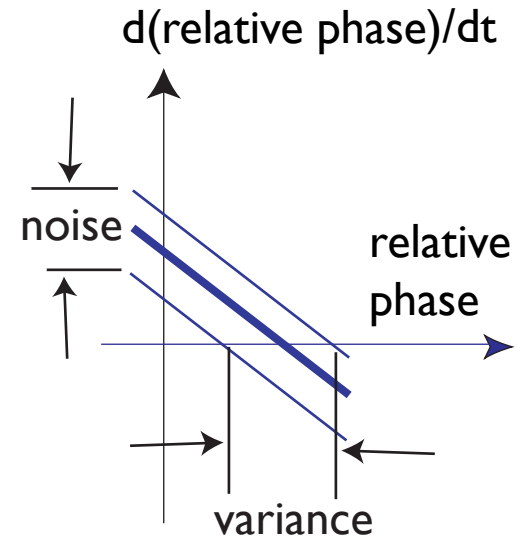
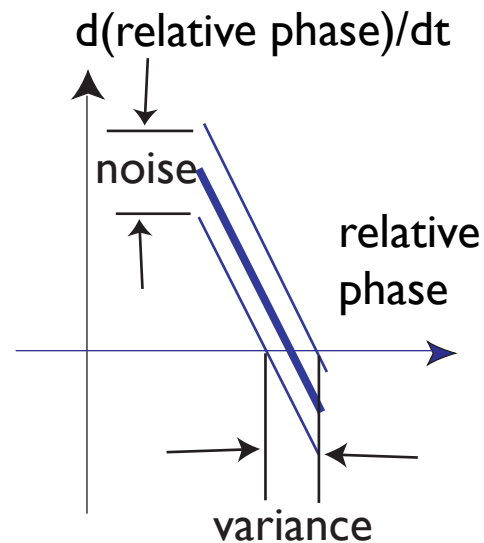
■ at increasing frequency stability of anti-phase is lost



# Predicts increase in variance

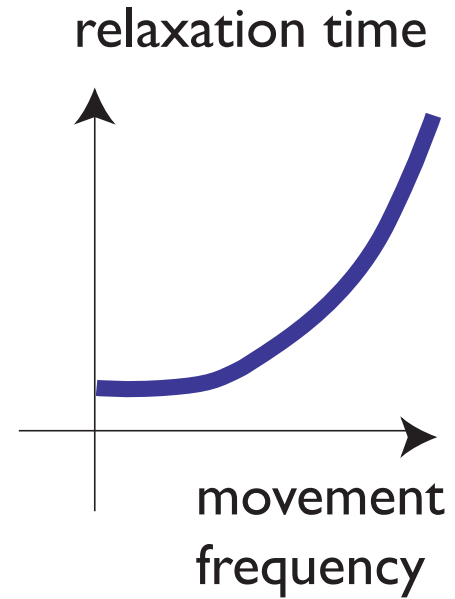
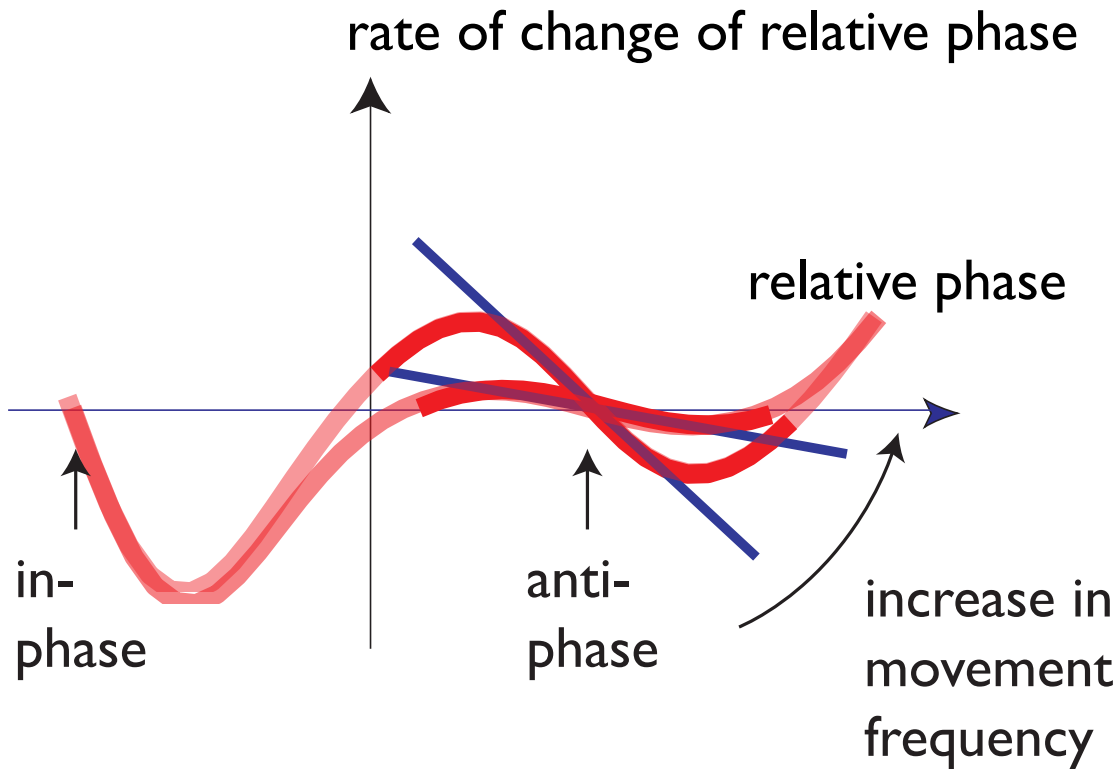


■ “critical fluctuations”



# 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**

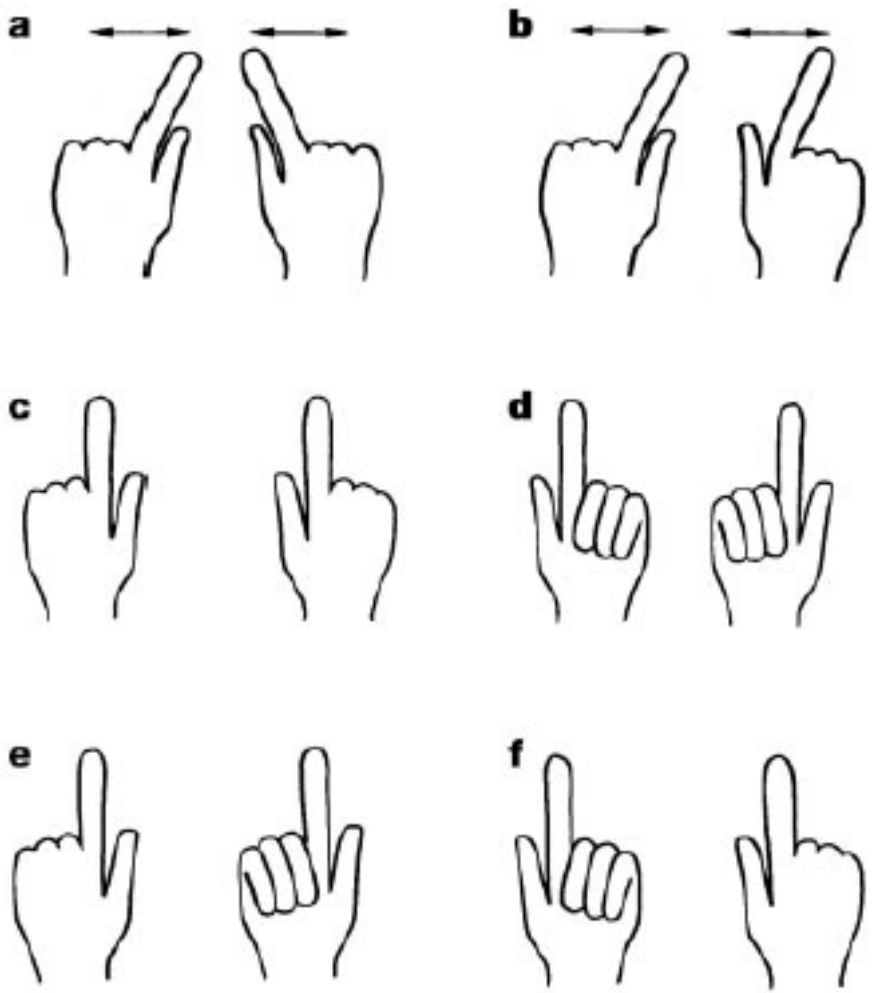
# What level does the instability of coordination come from?

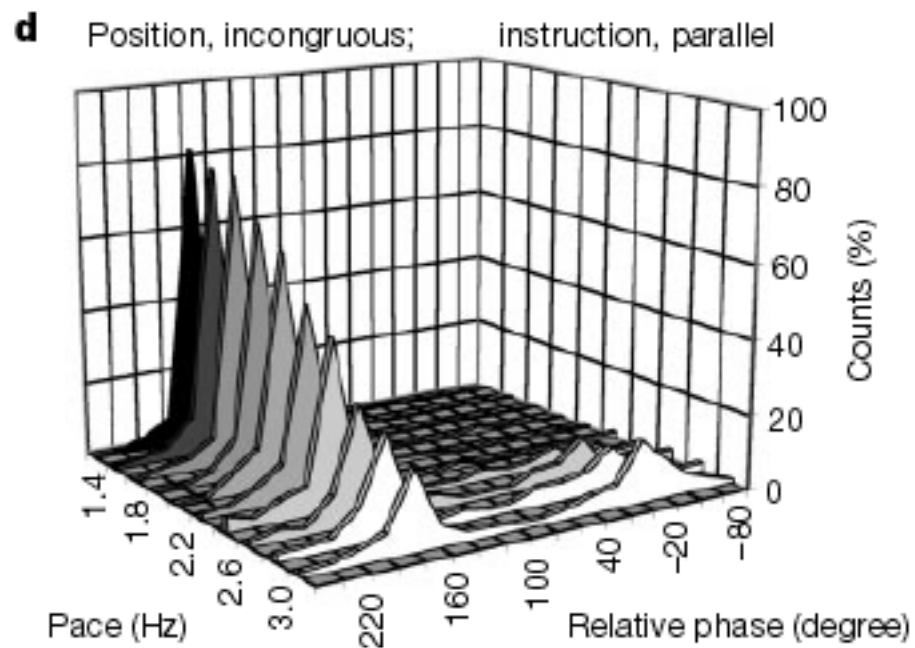
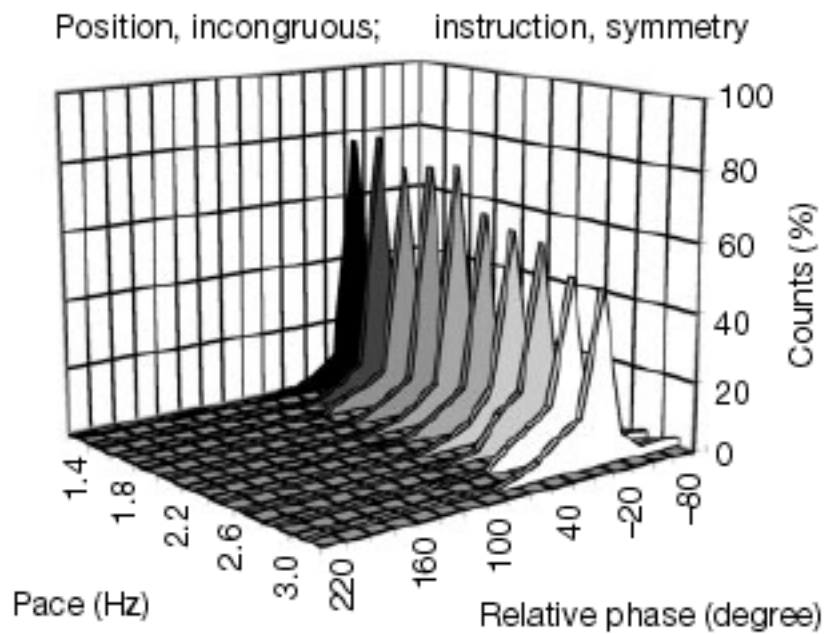
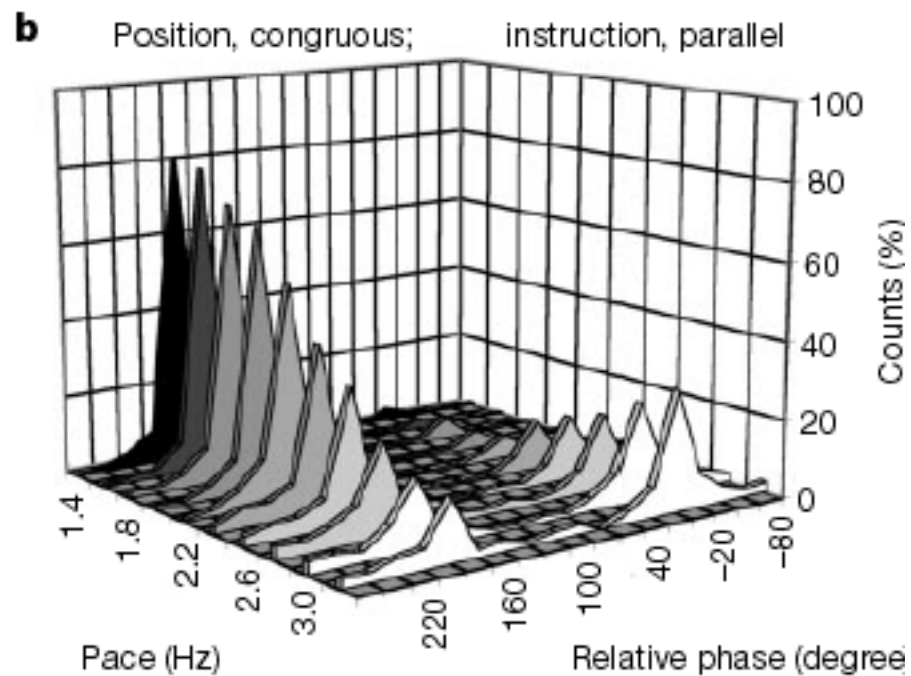
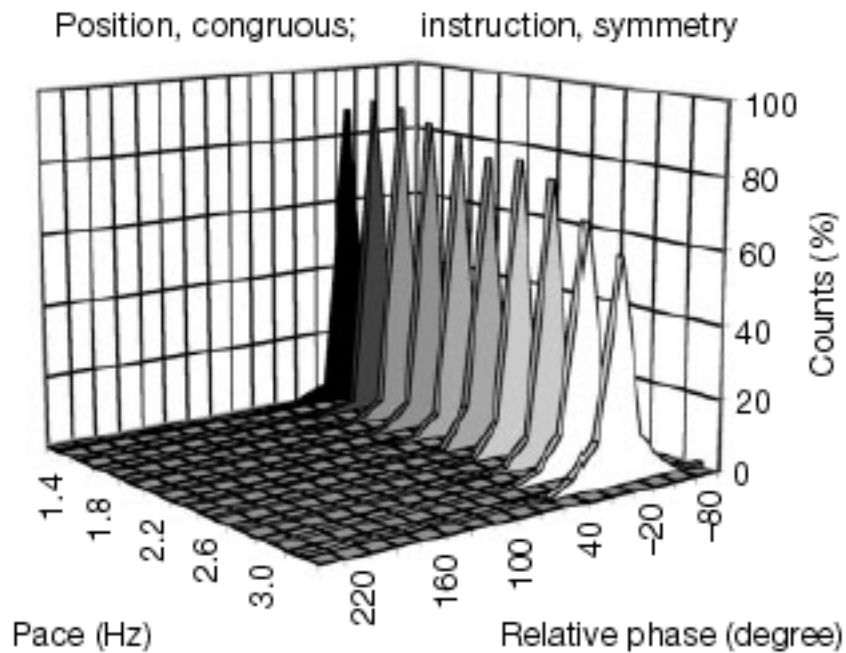
- from peripheral motor control?
- from central motor control?
- from perceptual representations of movement?



# What level does instability come from?

Is the instability tied to the motor system?



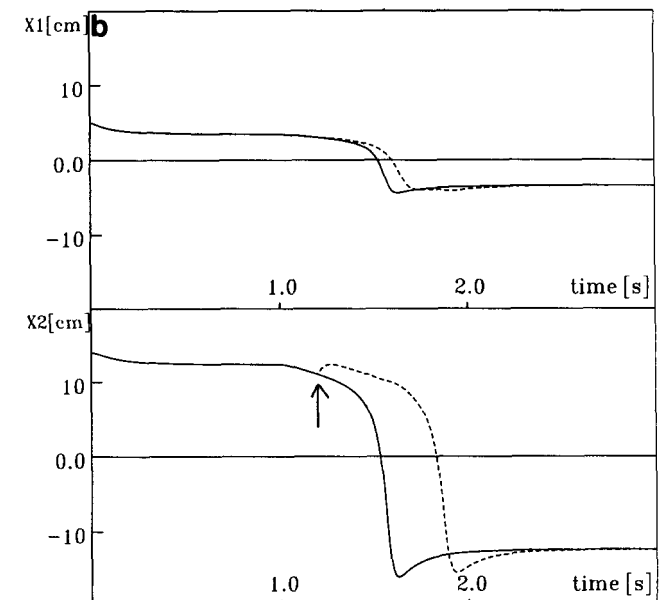
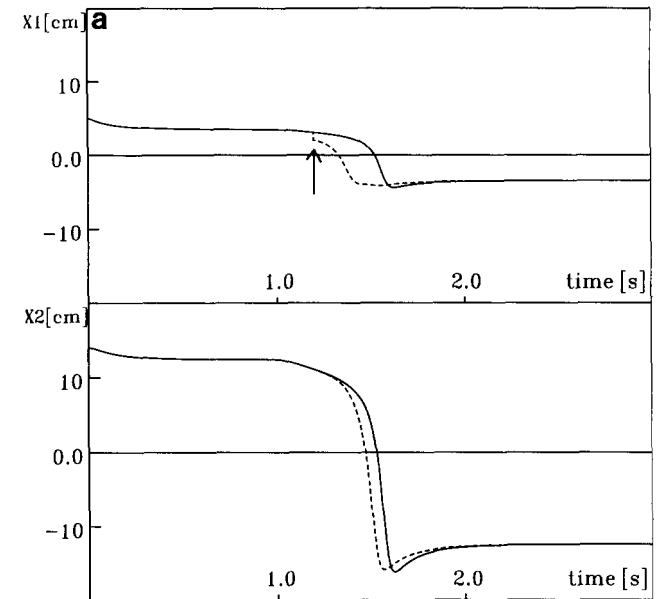


=> coordination in space

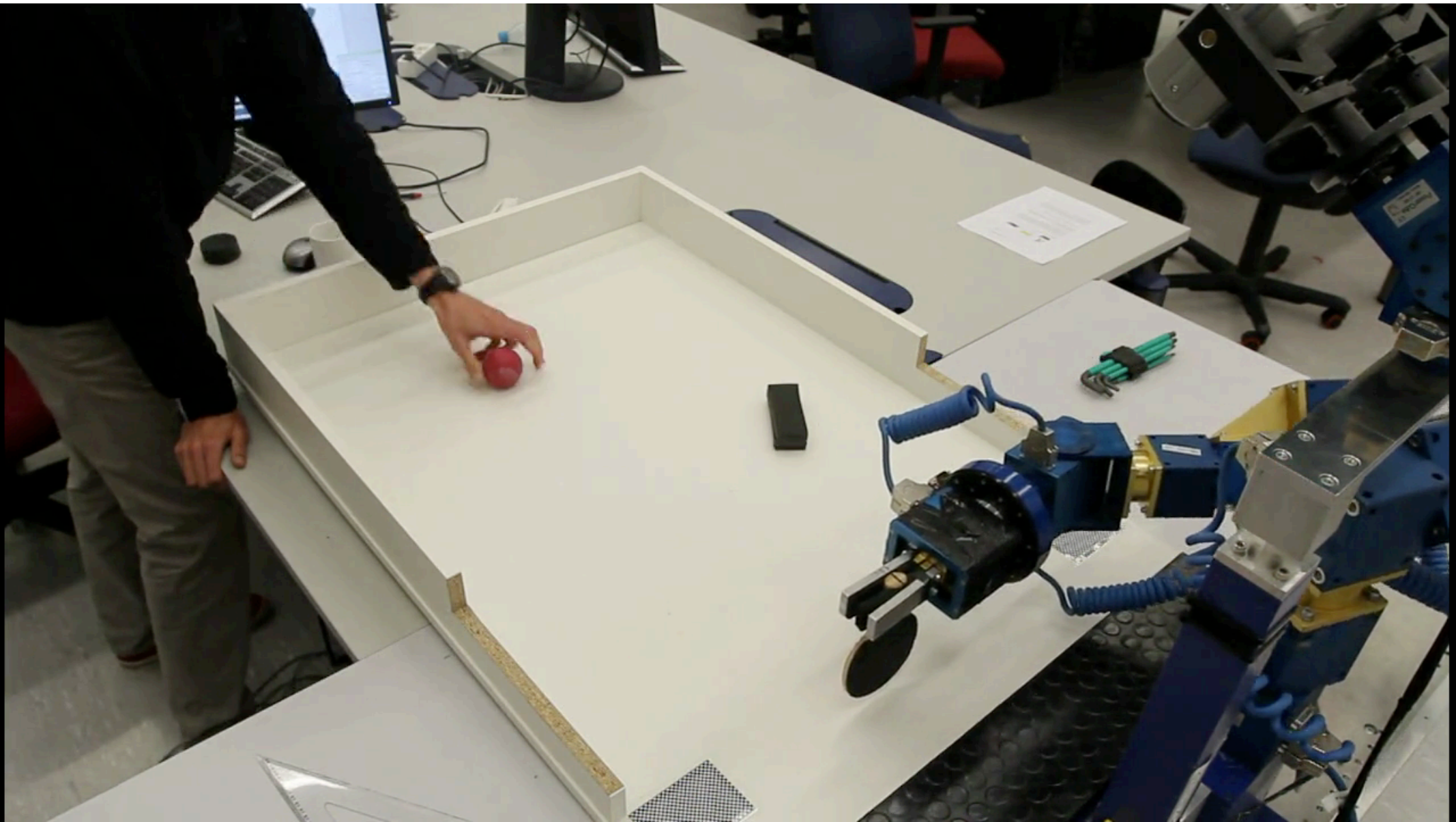
- rather than in effector space
- so coordinated oscillators are central
- rather than peripheral

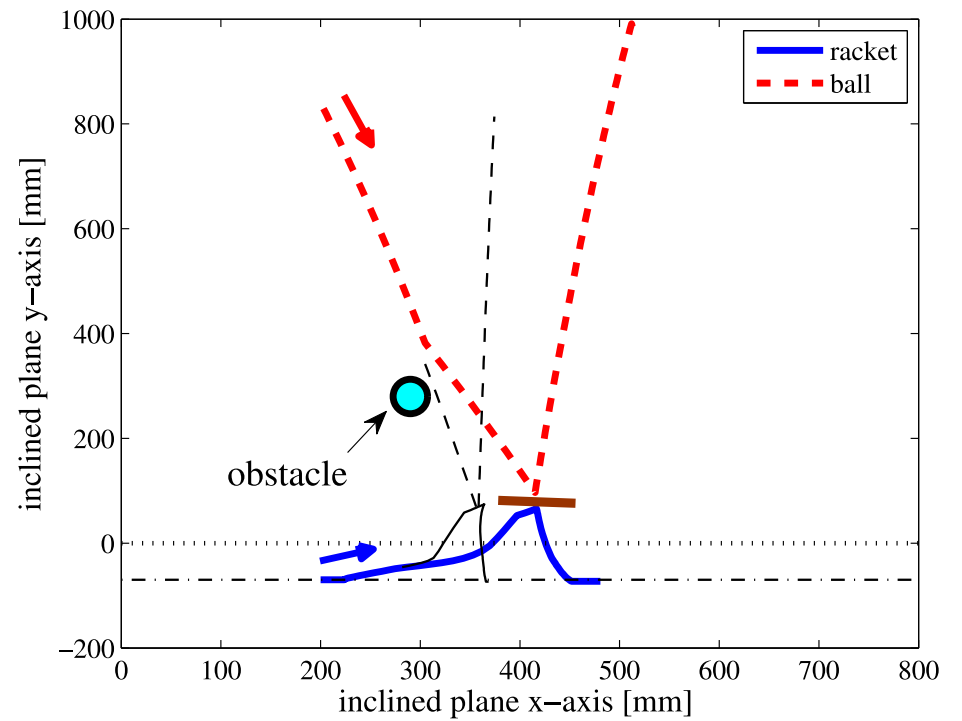
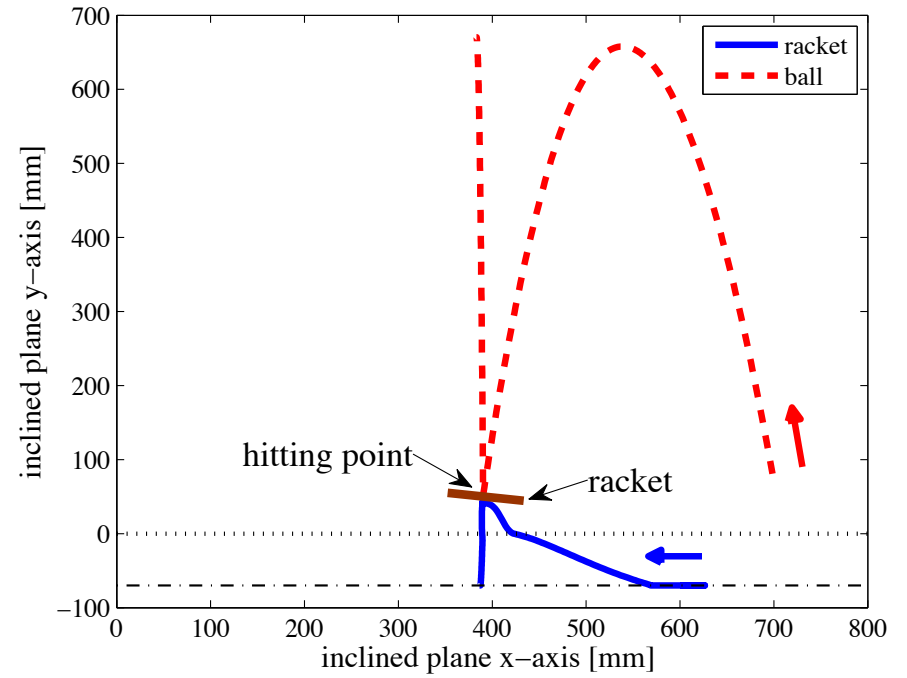
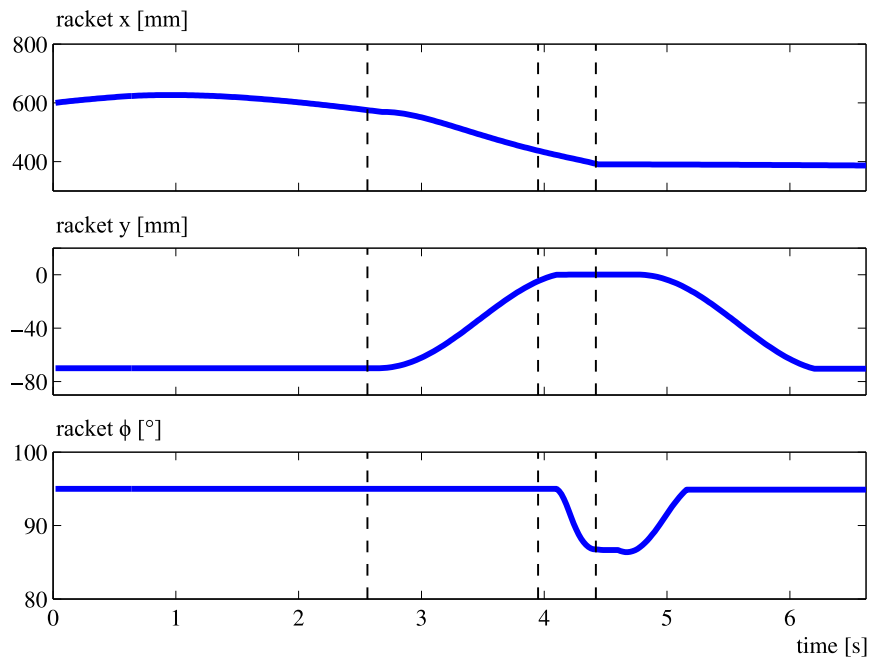
# Coordination of discrete movement

- 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



# 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