Toward a neural dynamic architecture of the motor system

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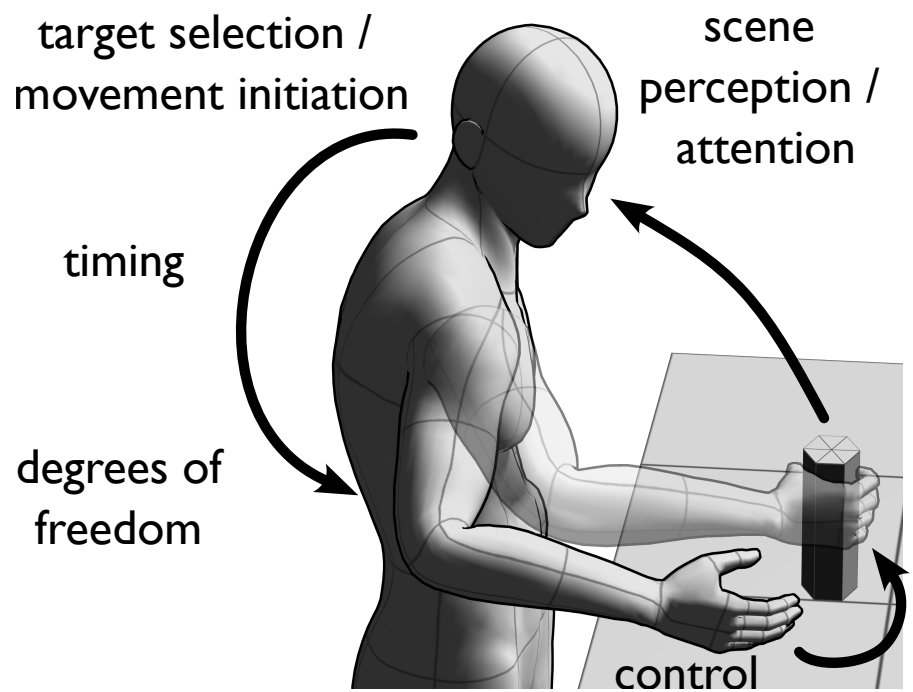
Reaching movements directed at objects

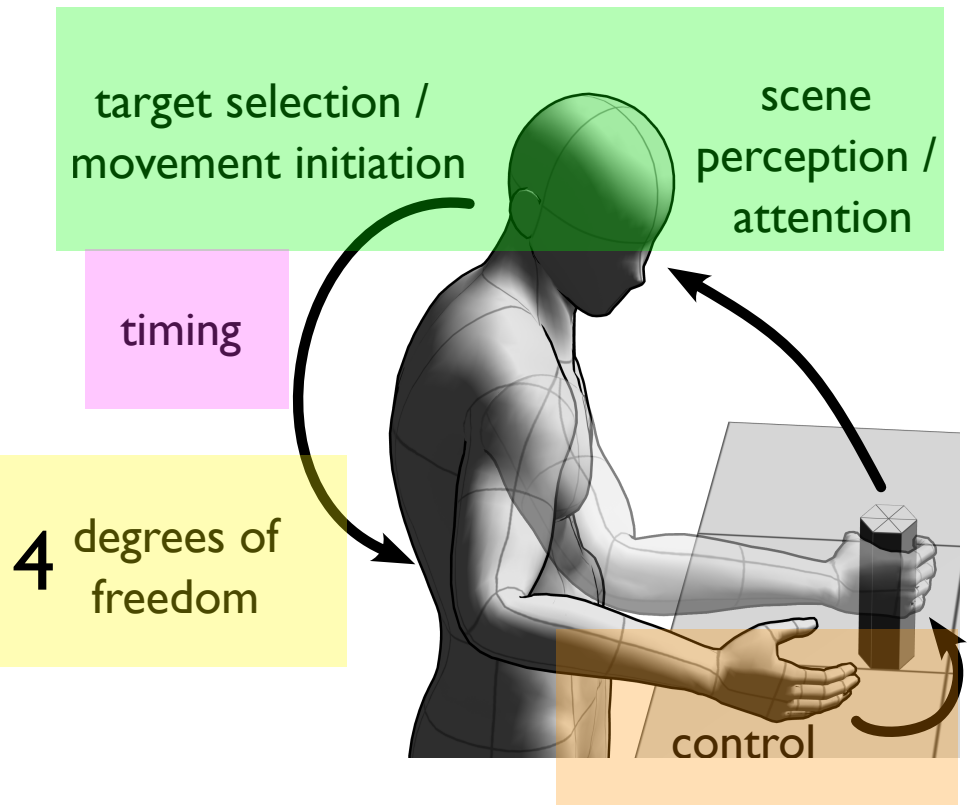
- exemplary model case for movement generation
- as it entails "everything"… perception, cognition, action, even goal orientation
- all these component processes interact… the key challenge of understanding movement generation



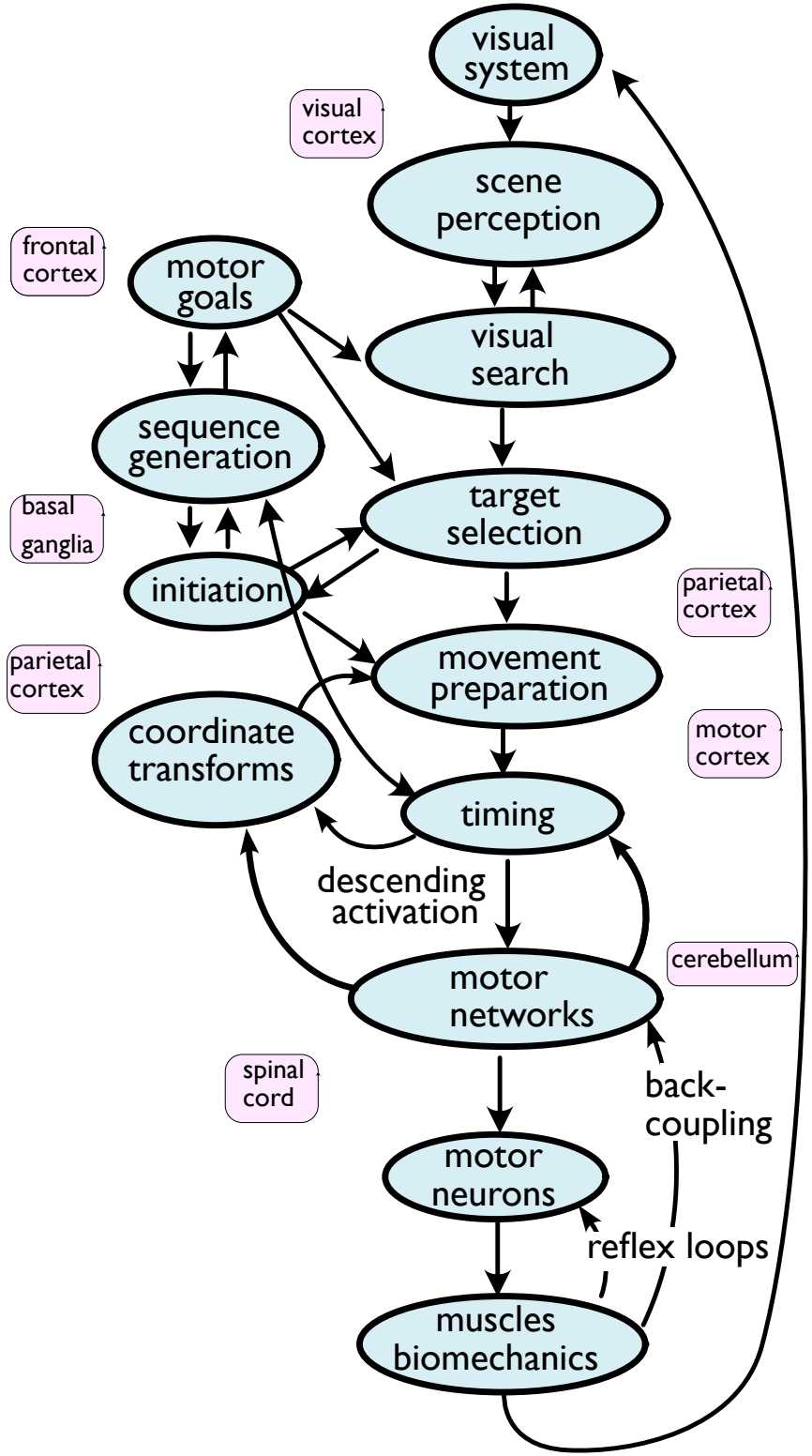
Levels of movement generation

interdependent

- 1 planning
  - movement preparation…
- 2 timing:
  - generate time courses of neural activation
- 3 control
  - activate muscles to generate the forces that bring about the movement



A functional/neural architecture of movement generation



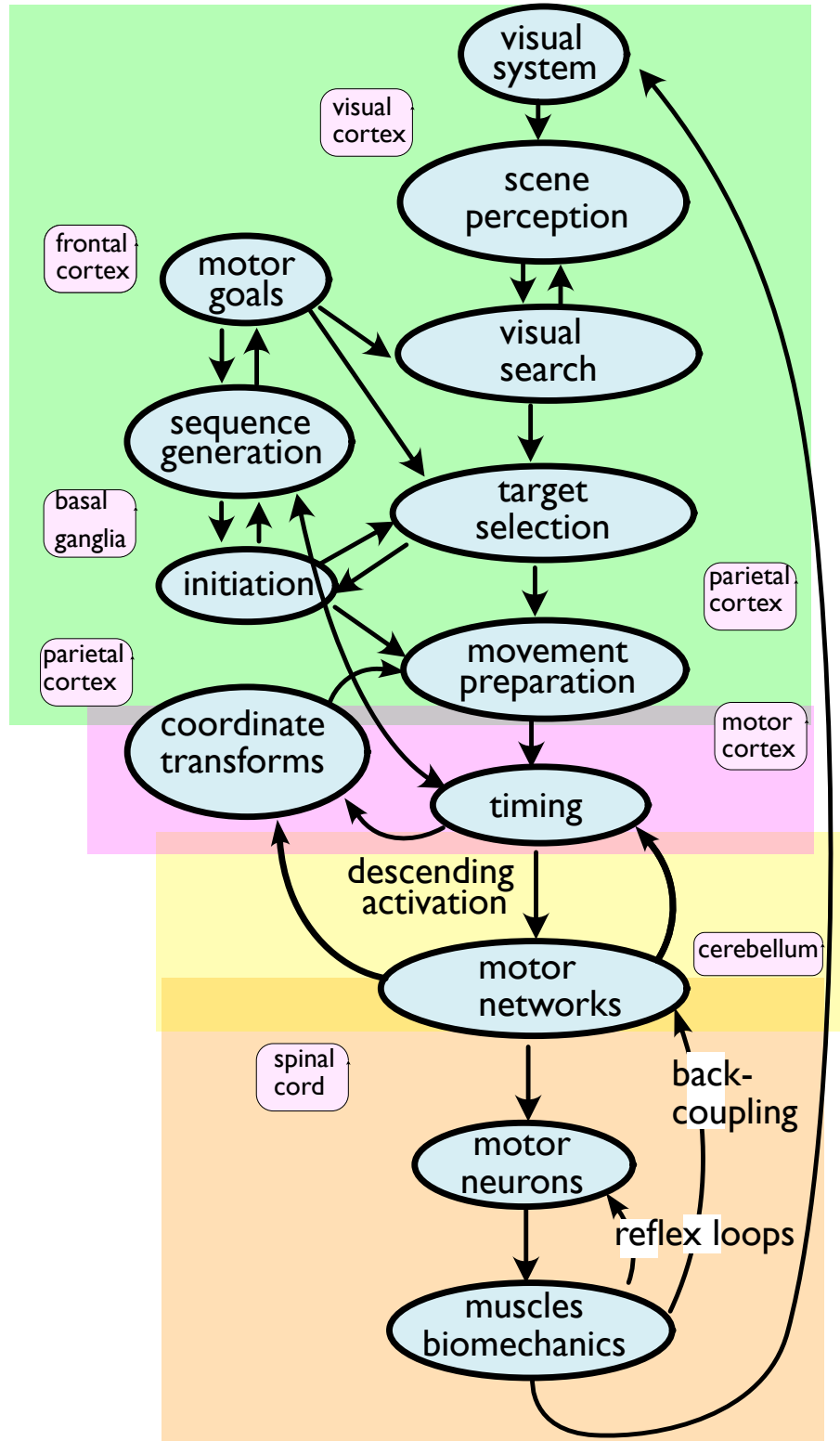
A functional/neural architecture of movement generation

planning

timing

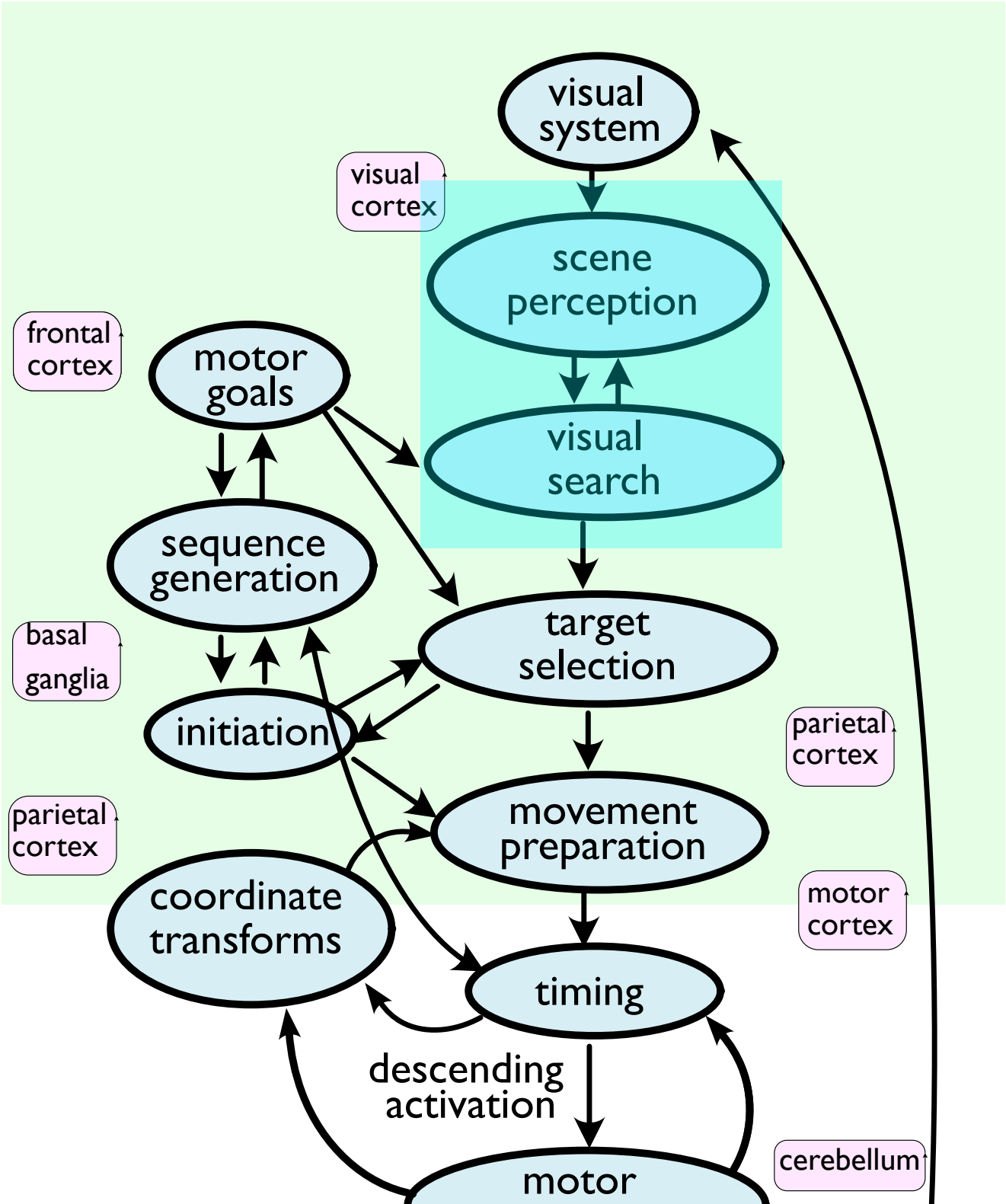
degree of freedom problem

control



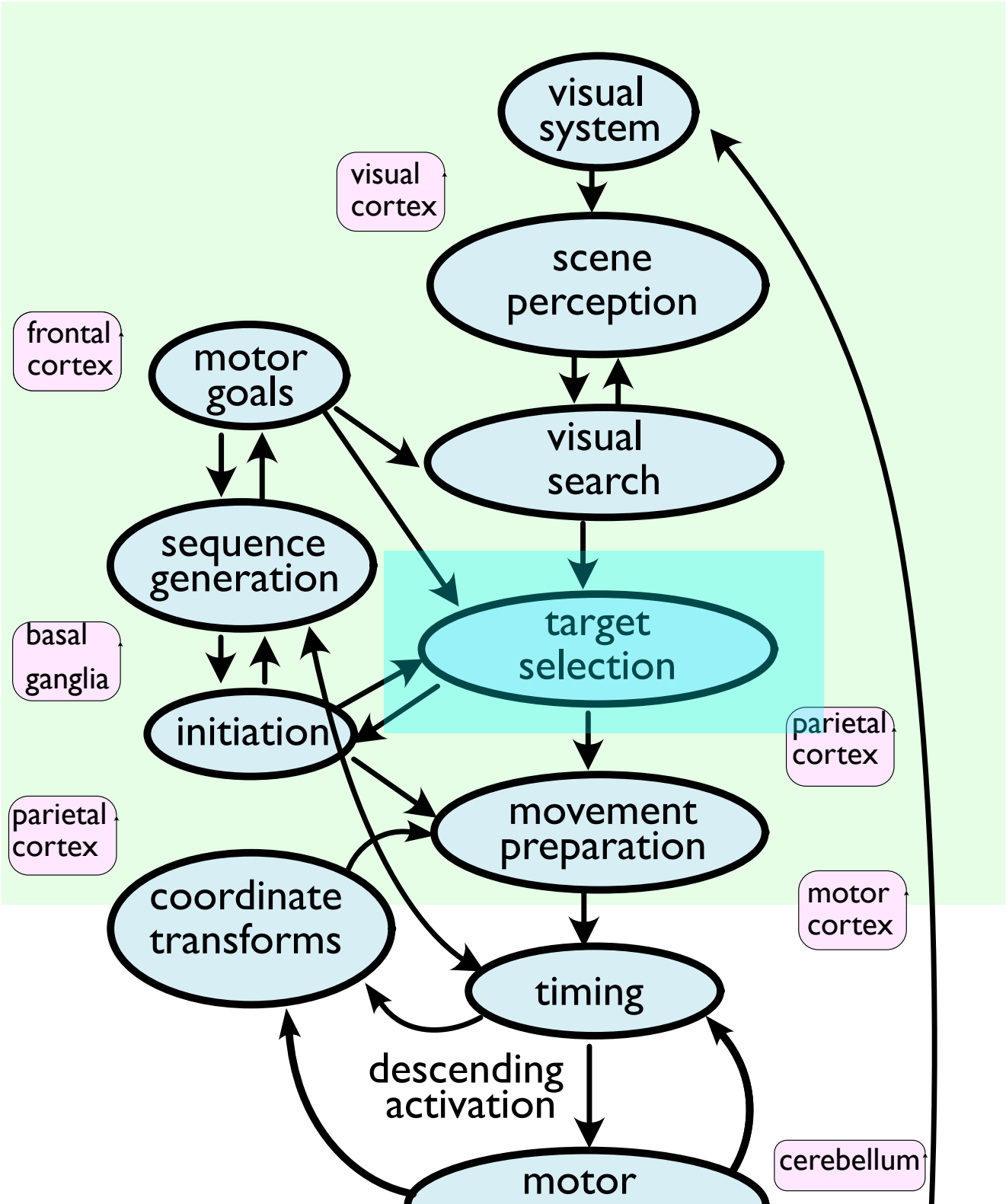
Visual search/ scene perception

planning

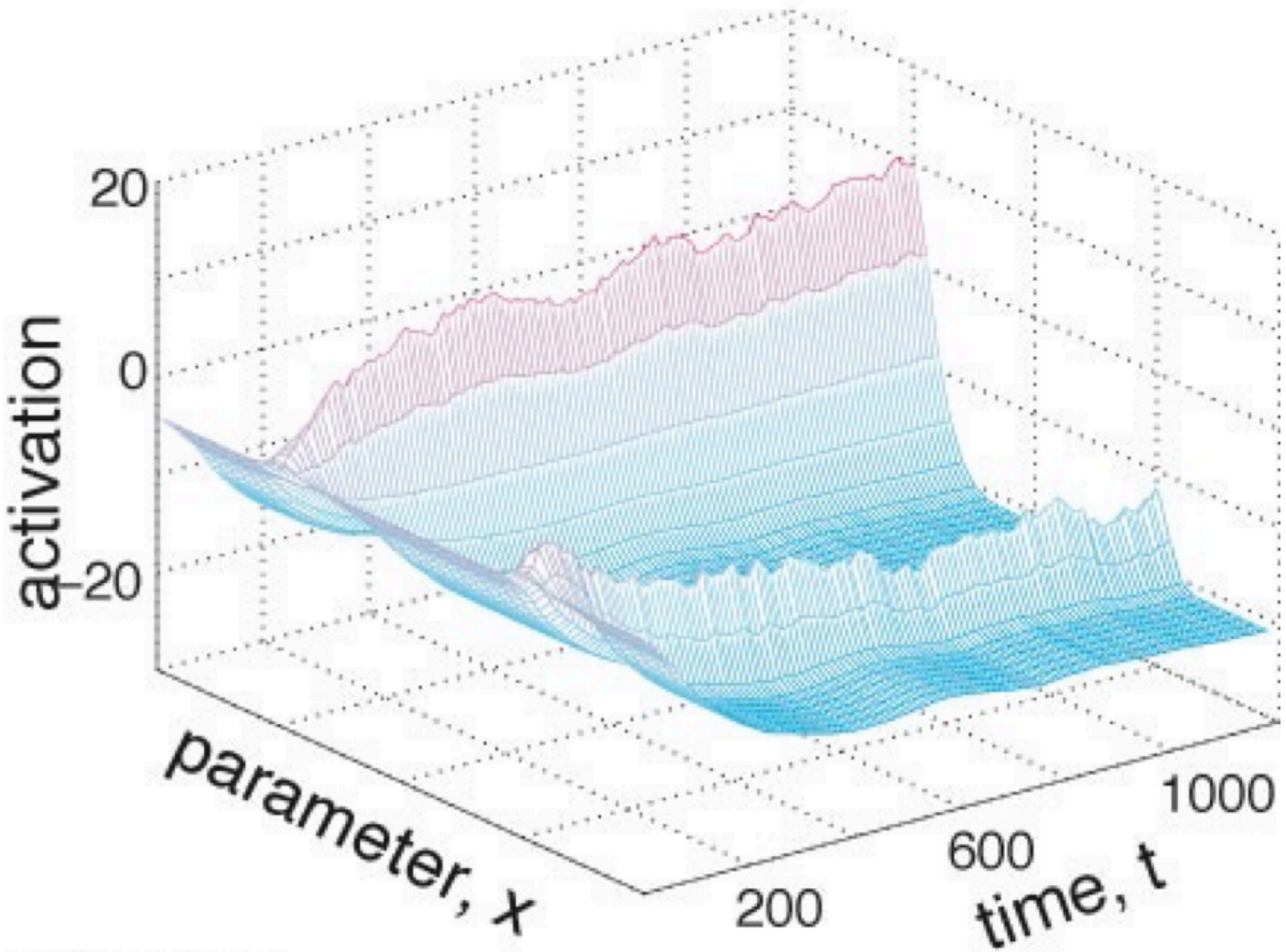


Target selection

planning



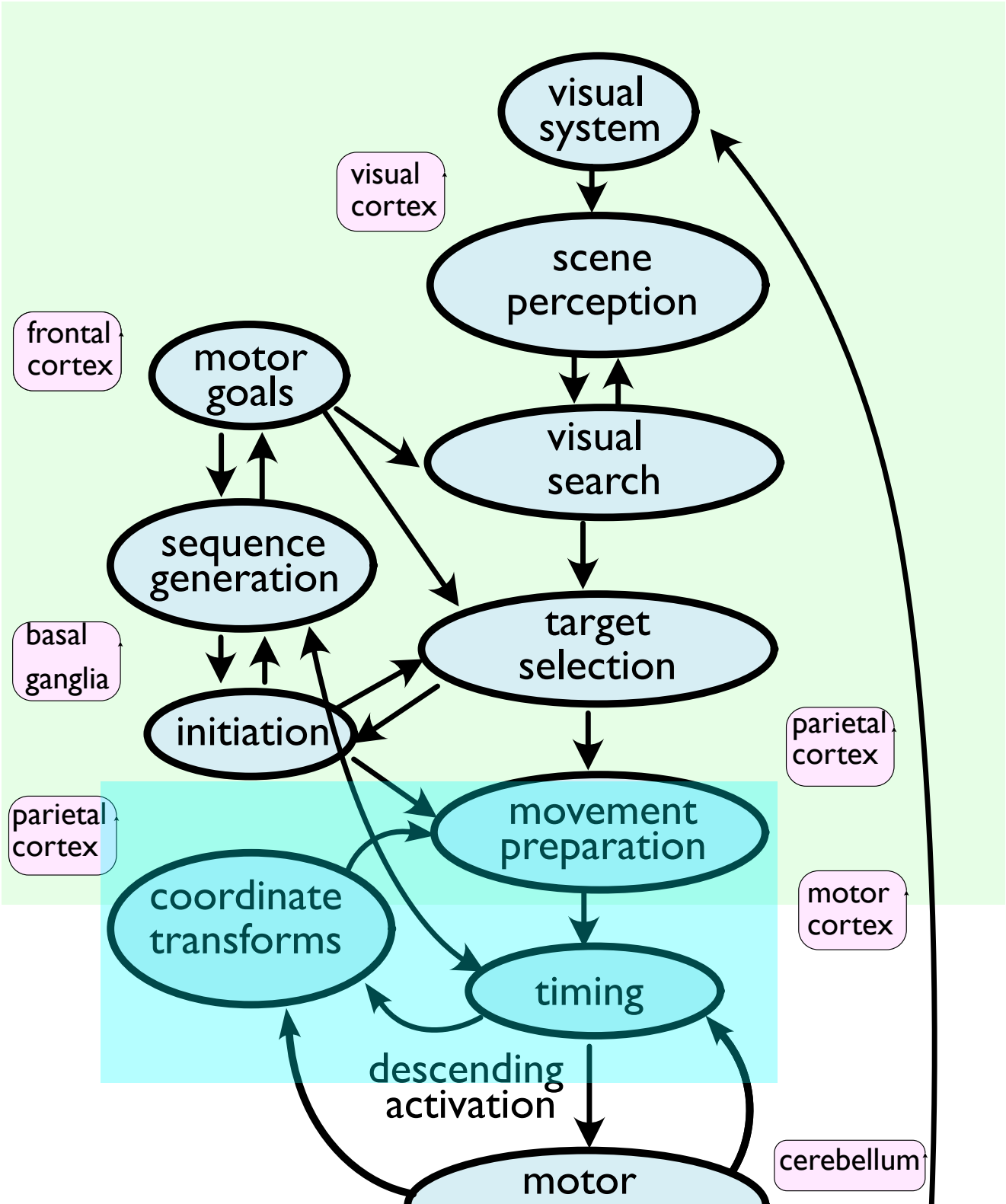
DFT model of target selection



[Erlhagen, Schöner, 2002]

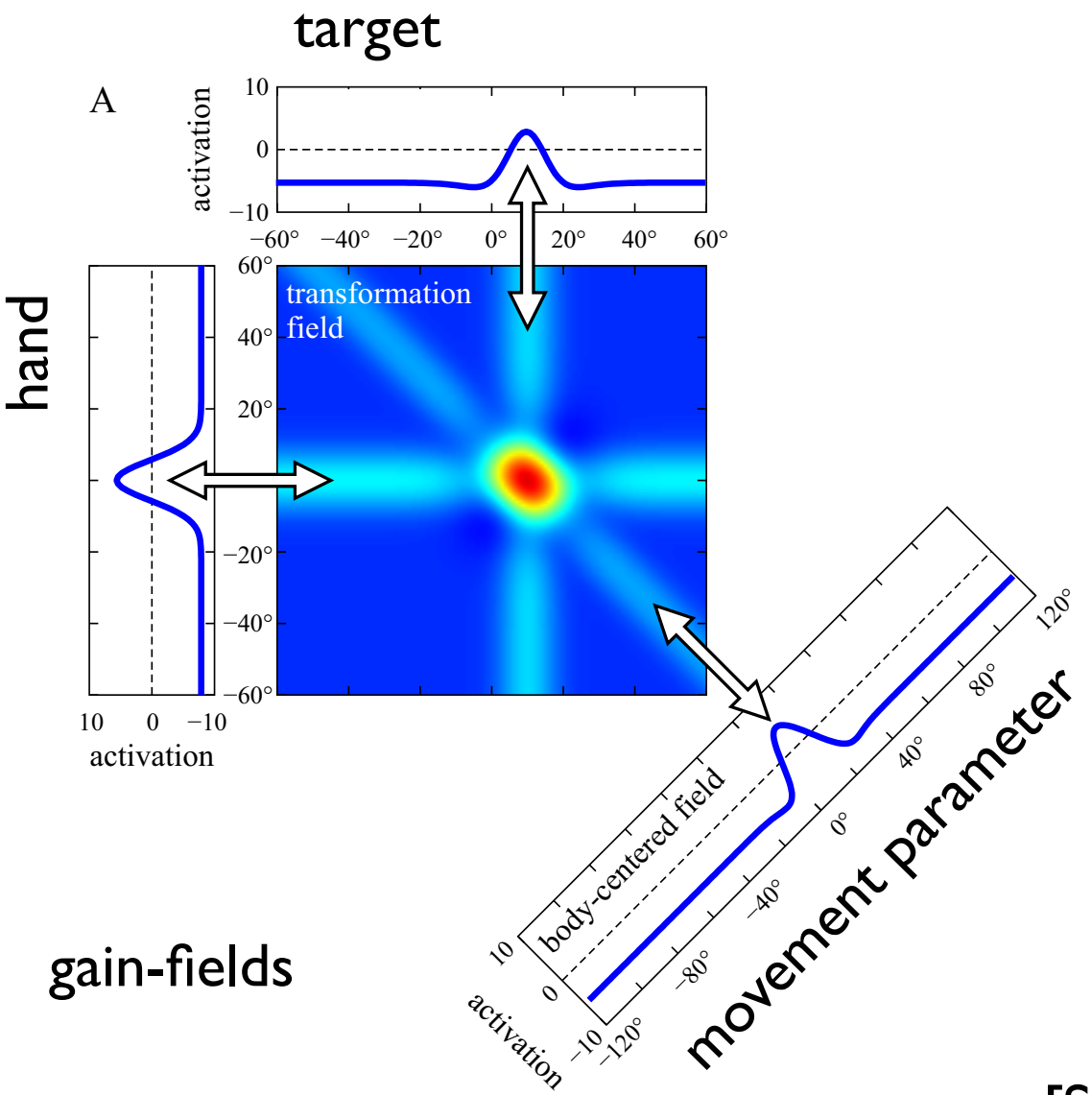
coordinate transforms / movement parameters

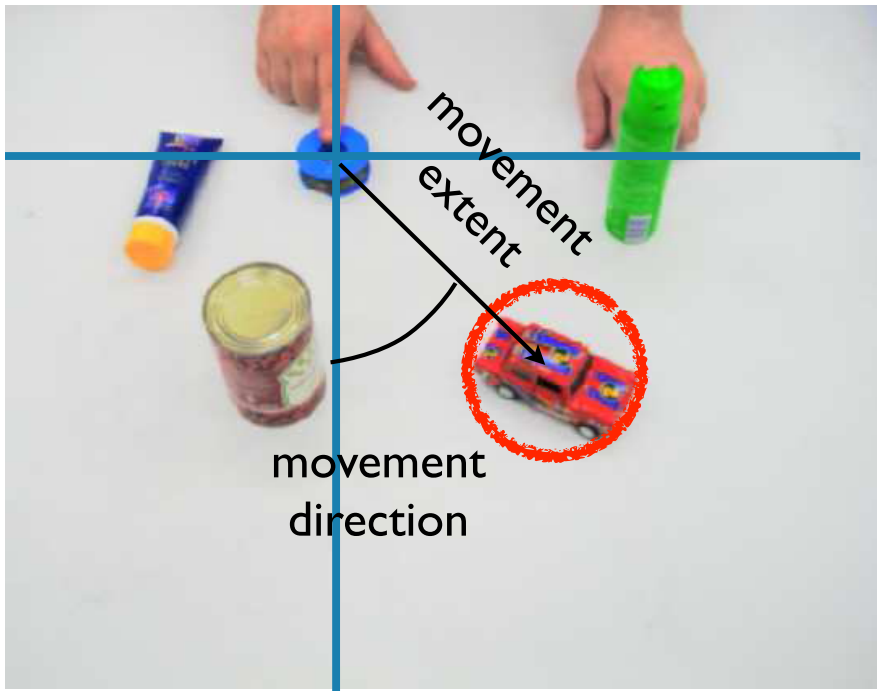
planning



Movement parameters from targets

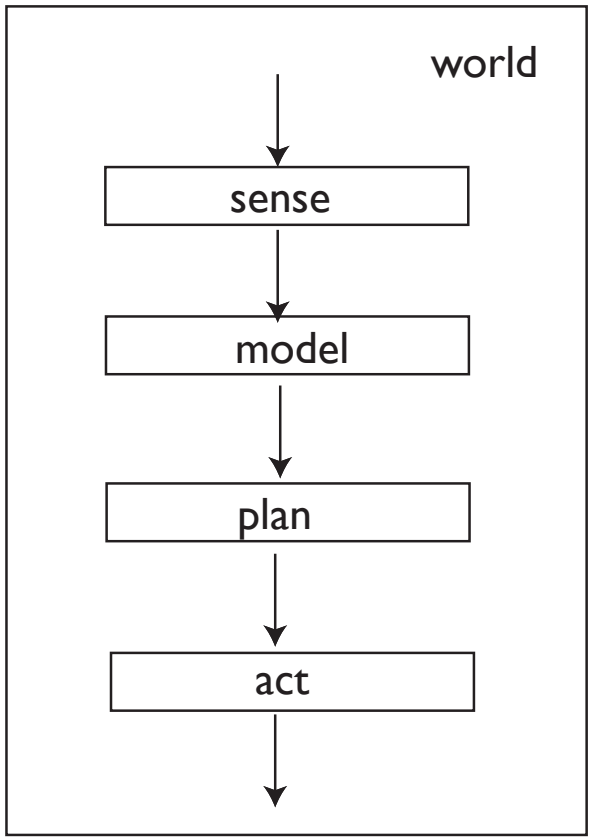
- based on initial position of the hand



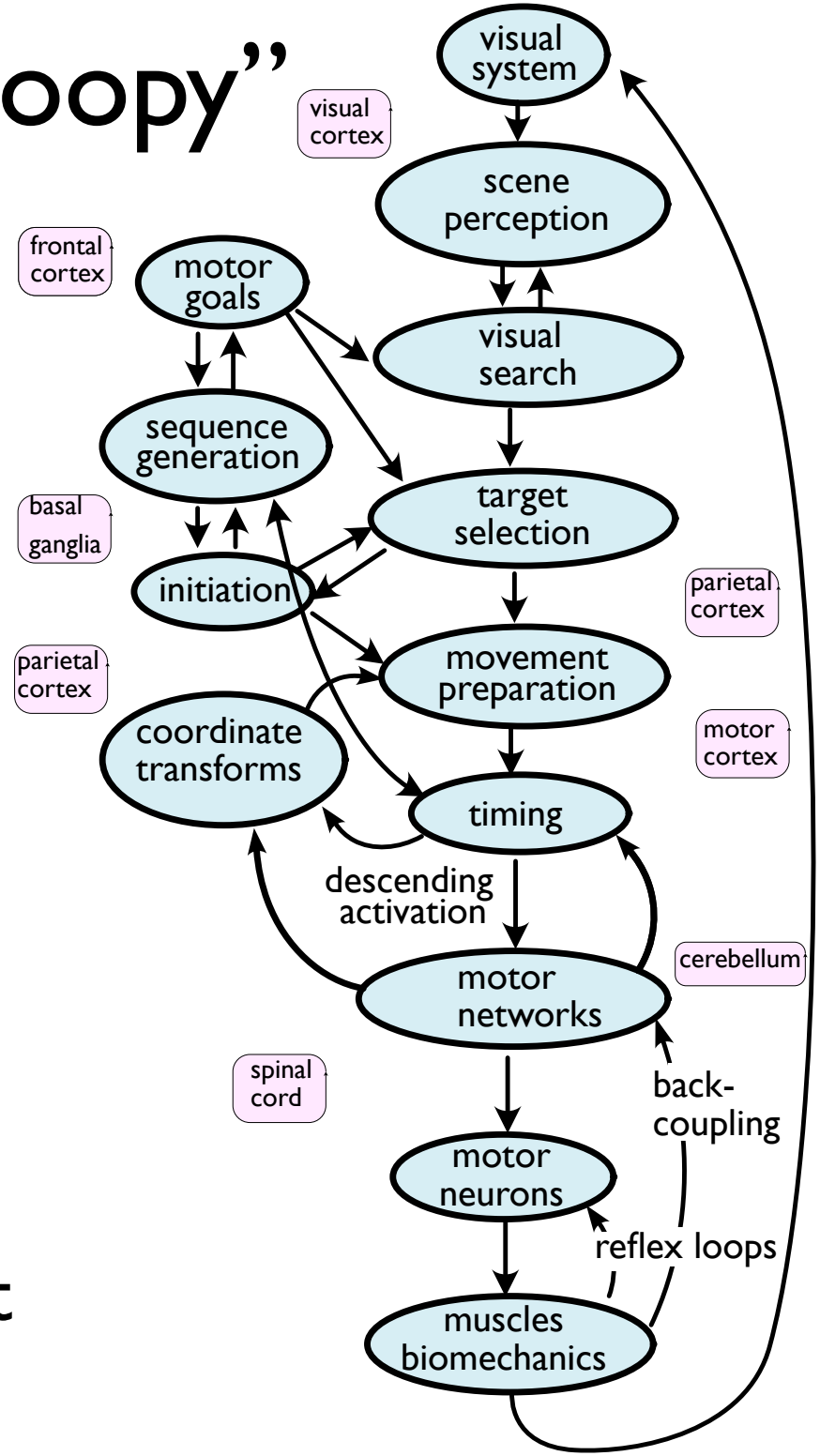


[Schneegans Ch 7 of *DFT Primer*, 2016]

Feed-forward



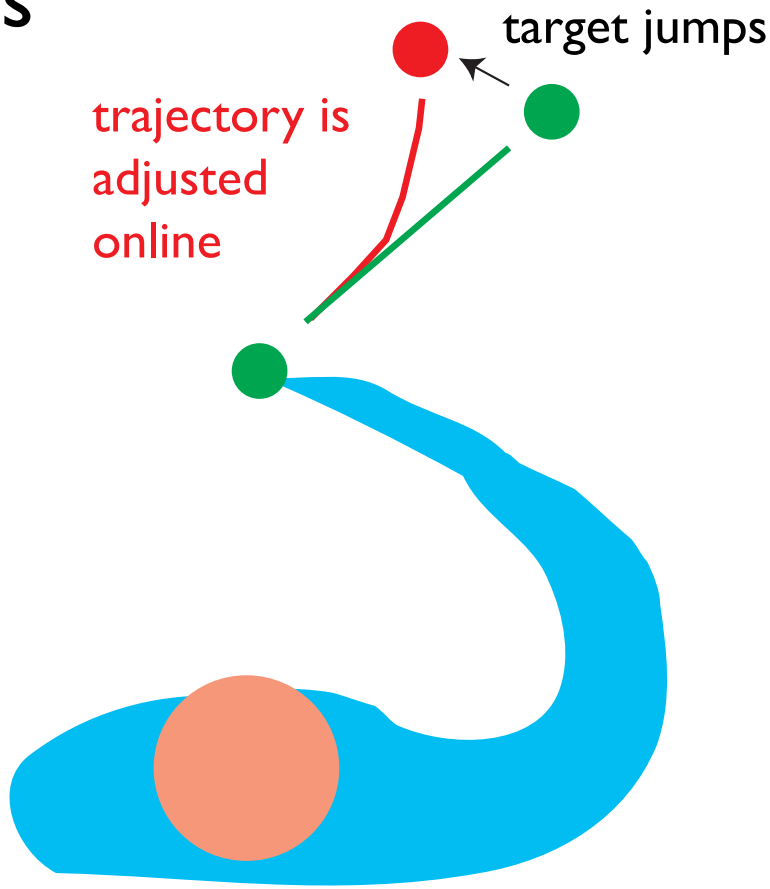
"Loopy"



- modules are continuously coupled: online updating
- and hand down activation, not "information"

Online updating

- movement parameters can be updated online any time…
- with a time delay of about 100ms

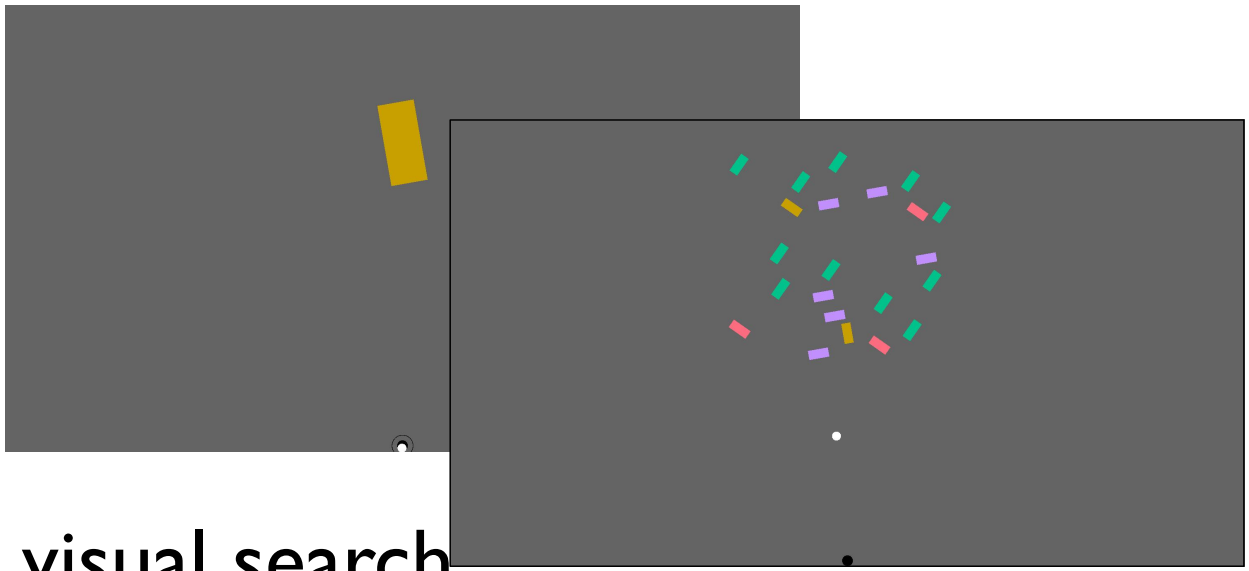


[Goodale, Prablanc, et al…]

Online updating: mouse tracking

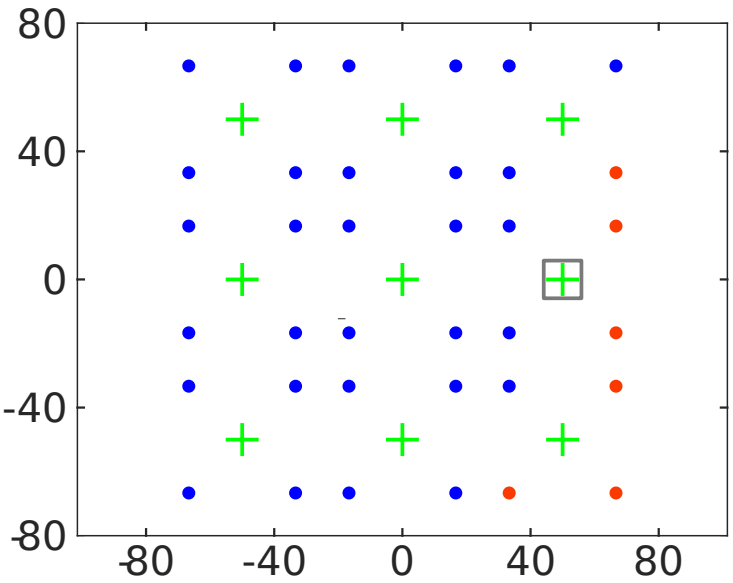
- observe the time course of selection …

A



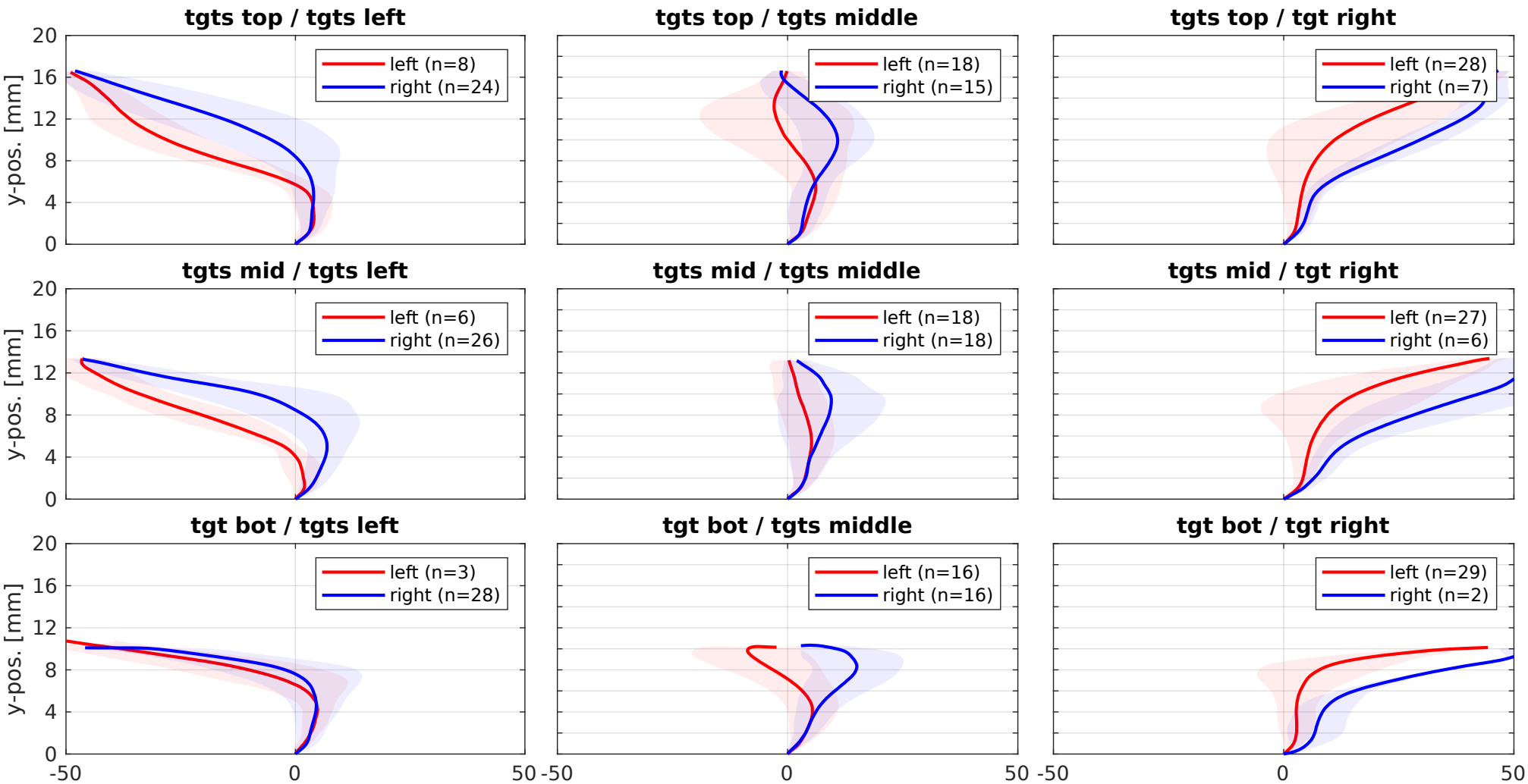
visual search

B

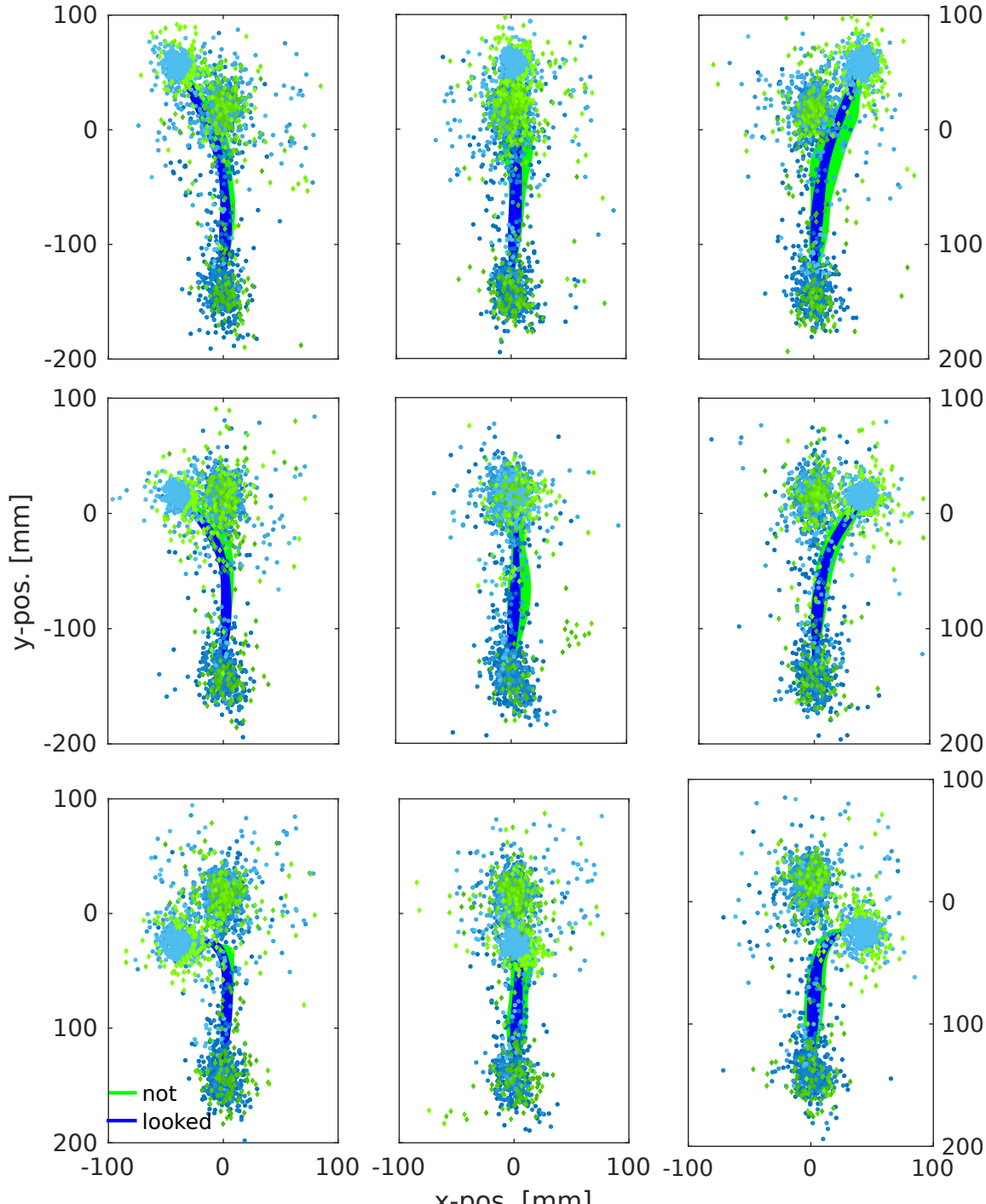


[Hummert dissertation, 2022]

Online updating and attraction to distractor



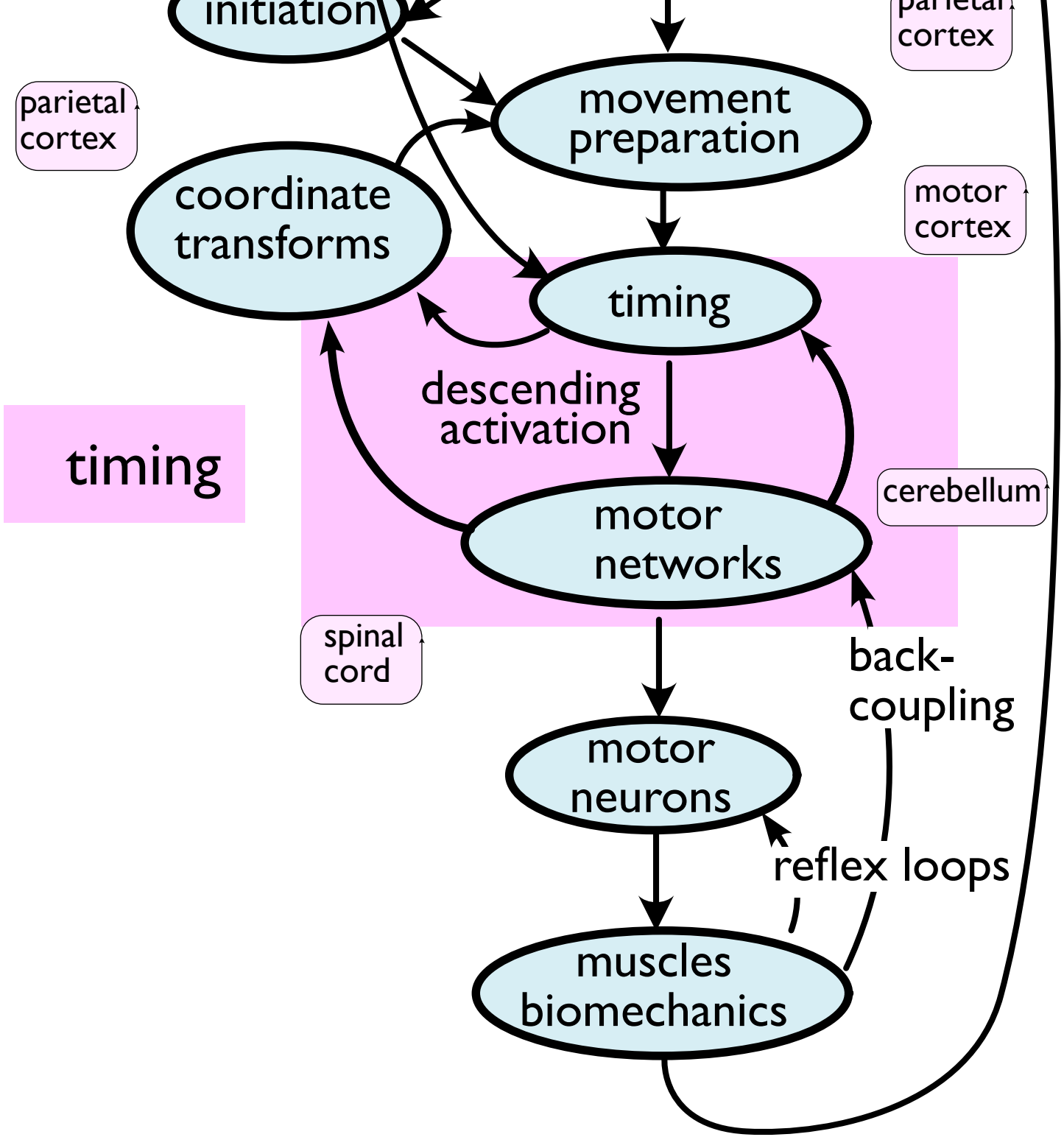
Attraction not explained by eye movements



Implications

- the mouse trajectory is updated online while visual search and target selection take place
- activation around the non-selected target is passed on to the movement generation system
- => “planning” and “control” are integrated
- this may be the basis for compliance

Timing


initiation
parietal cortex
parietal cortex
movement preparation
coordinate transforms
motor cortex
timing
descending activation
timing
cerebellum
motor networks
spinal cord
back-coupling
motor neurons
reflex loops
muscles biomechanics

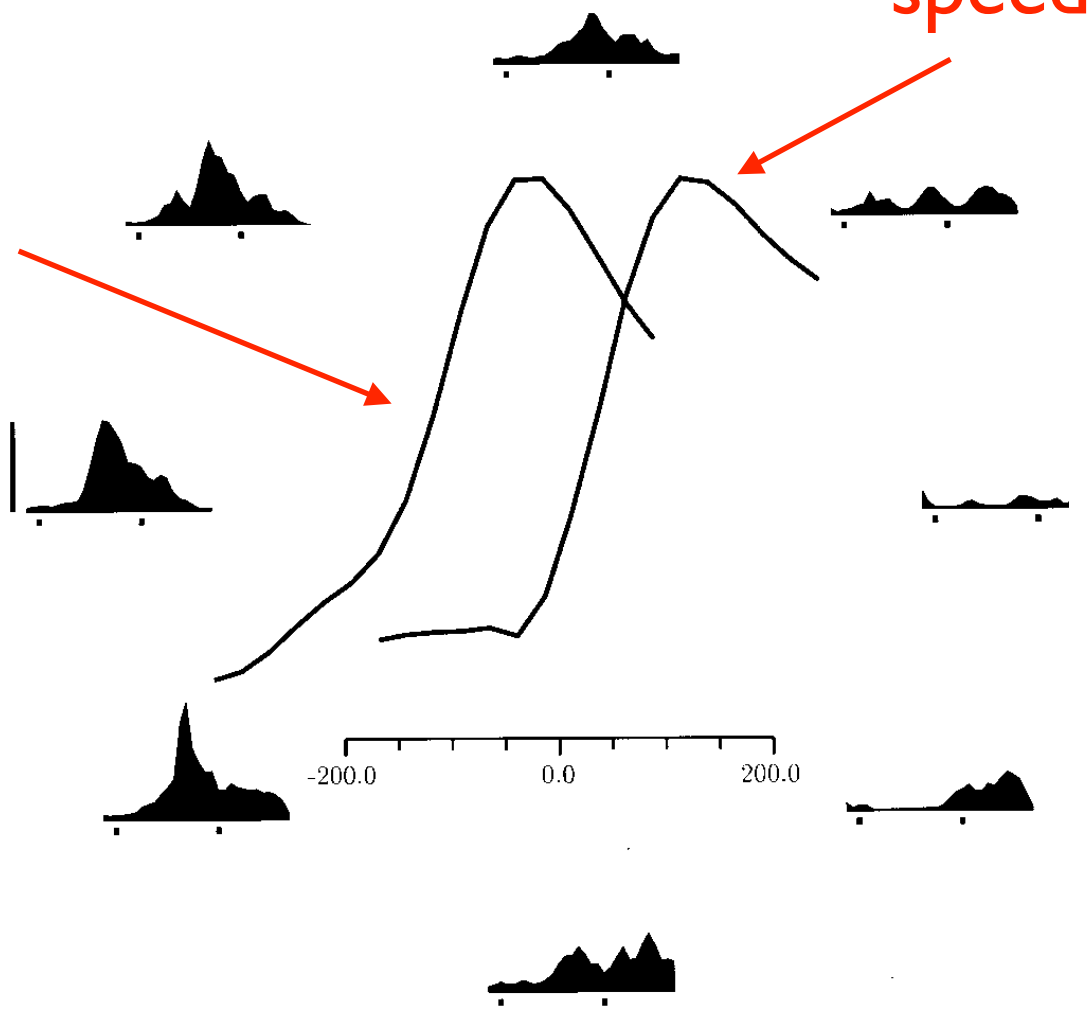
How is movement generated?

- autonomously… not "driven" by external input => neural activation patterns must be "self-generated"
- notion of neural timers: neural oscillators
  - although they may only do a single cycle of activation/ deactivation = active transient
- timing is highly constrained: hand must reach target with zero final velocity in a given time ("the optimal control problem")

Neural timers in MC

timing signal estimate from neural population

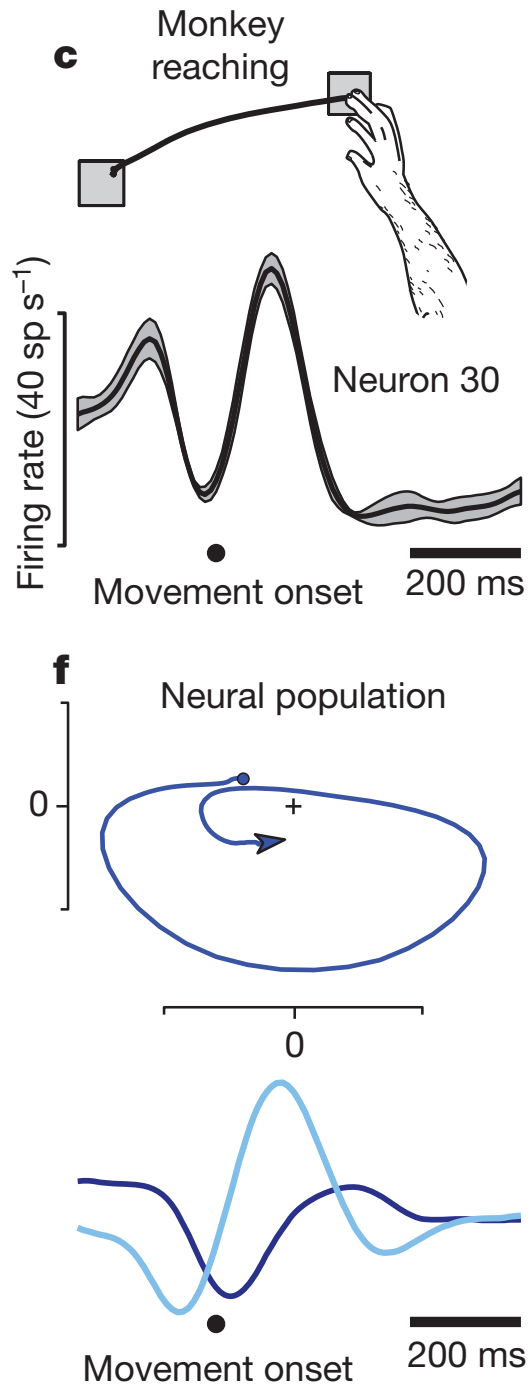
speed of hand



[Moran, Schwartz, J Neurophys 1999]

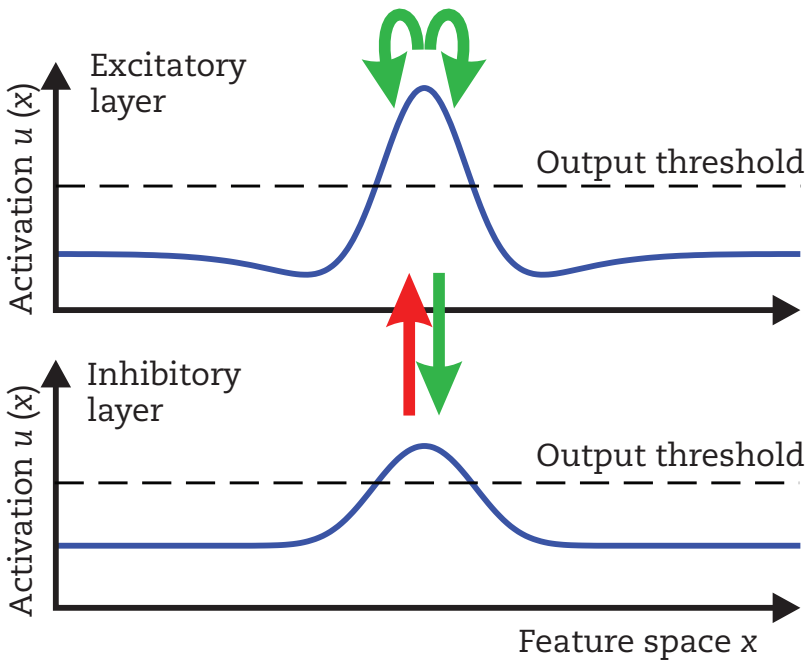
Neural timers in MC

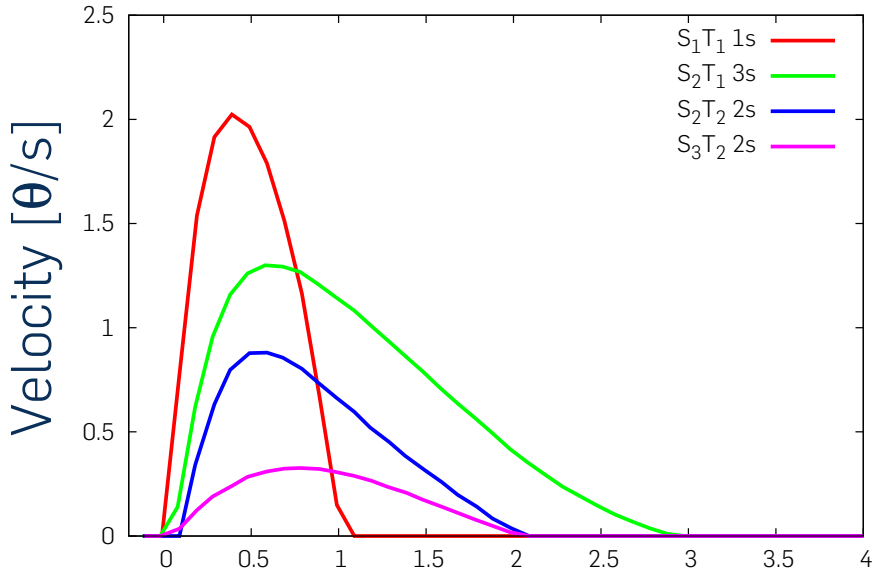
low-dimensional

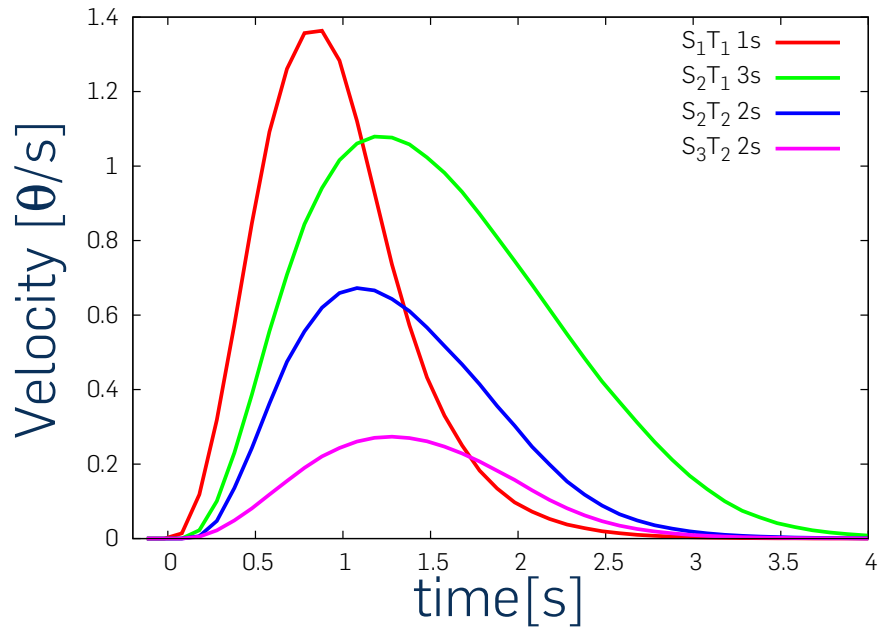


[Churchland et al., Nature 2012]

Neural timers are generic in neural dynamics



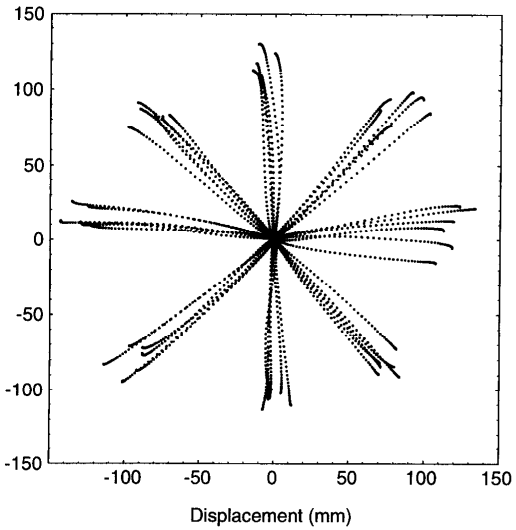




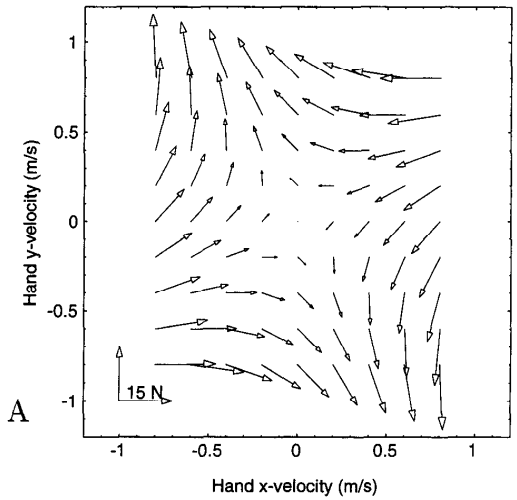
[Zibner, Tekülve, Schöner, 2015; Schöner, Tekülve, Zibner, 2019]]

Timing at low-dimensional /spatial level

- neural data…
- coordination of hand with events
- kinematic regularity of movement in hand space
- invariant under force-field learning

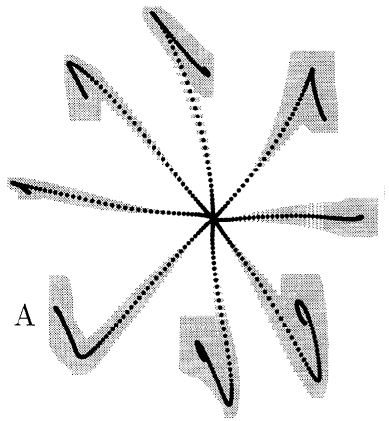


center-out movements
base-line

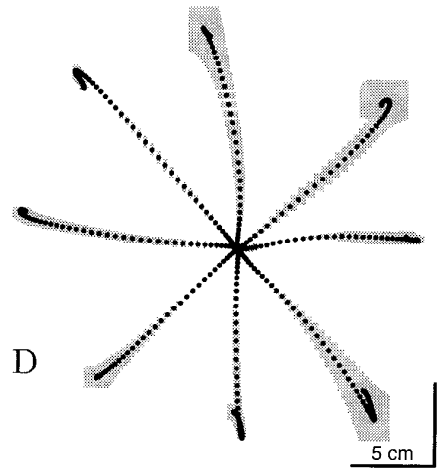


[Shadmehr, Mussa-Ivaldi, 1994]

velocity dependent force-field = zero at rest

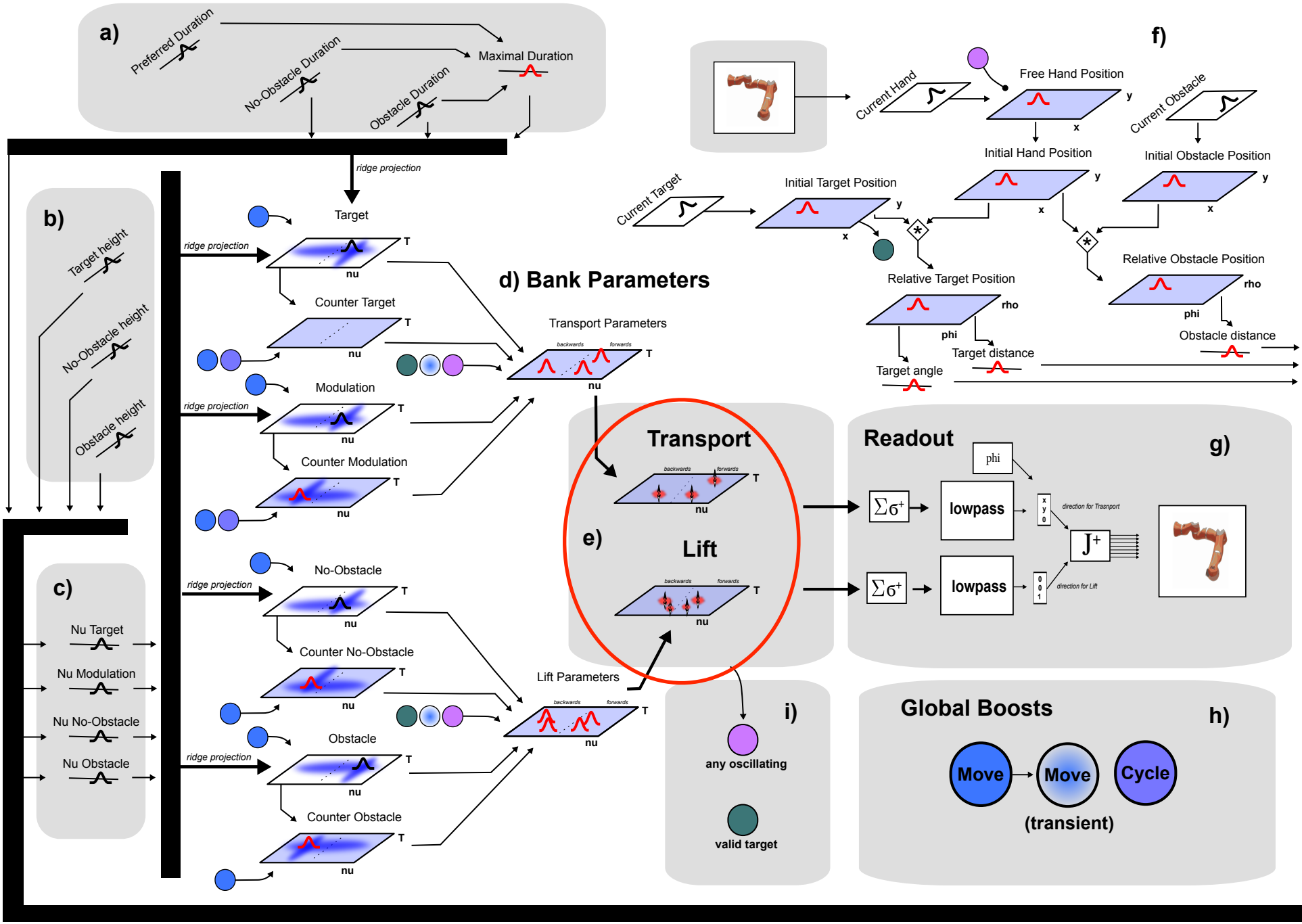


center-out movements before adaptation



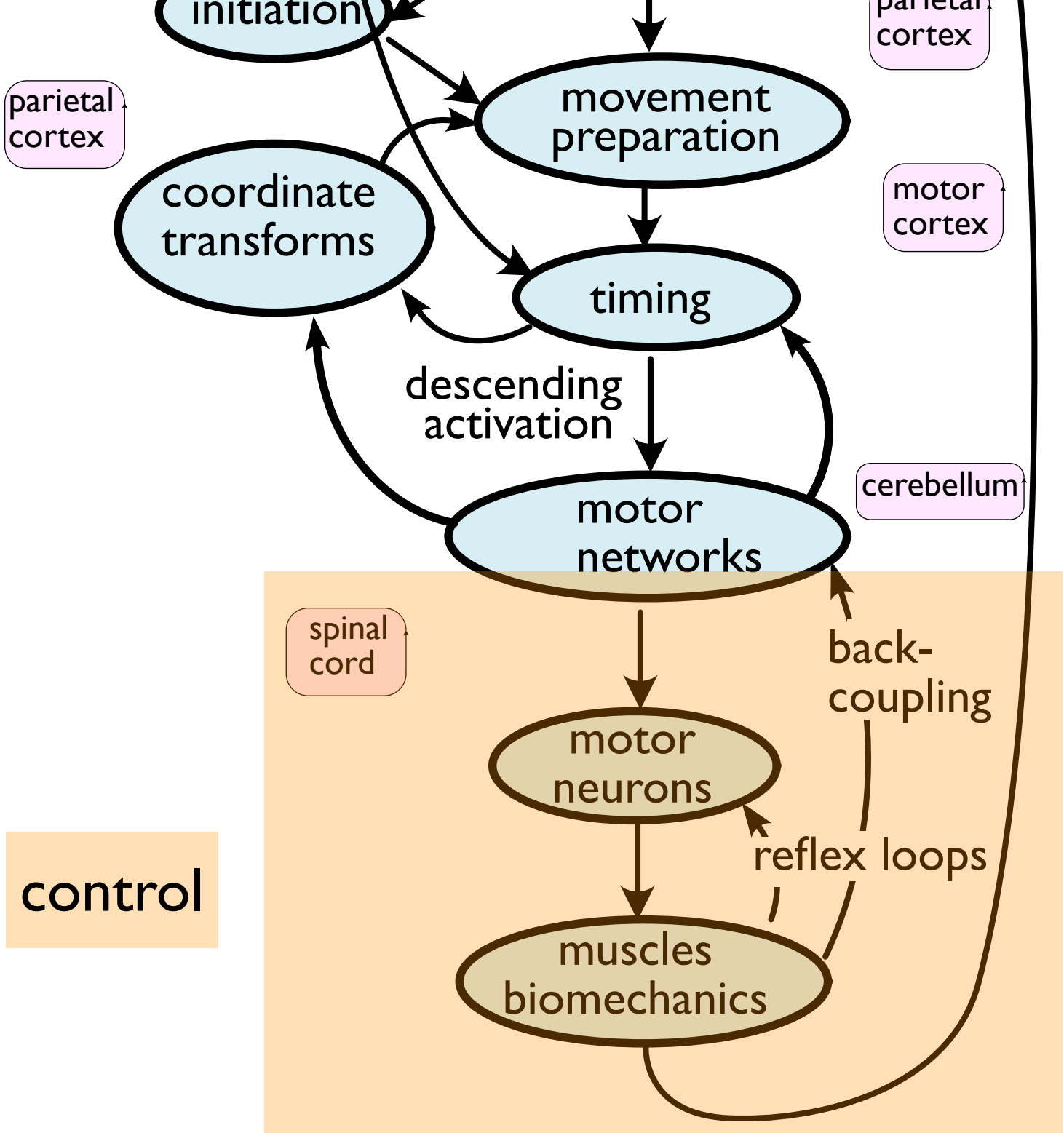
center-out movements after adaptation

Pools of neural timers



[Jean-Stéphane Jokeit, dissertation 2022]

Control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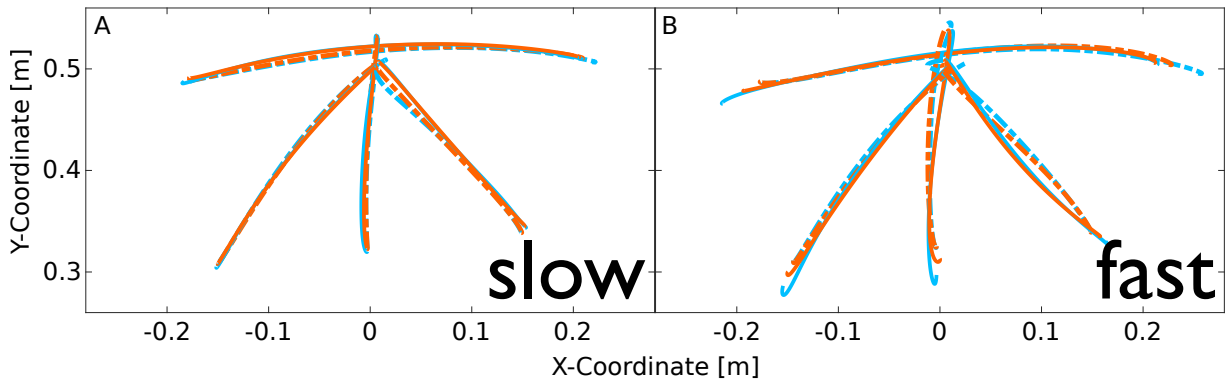
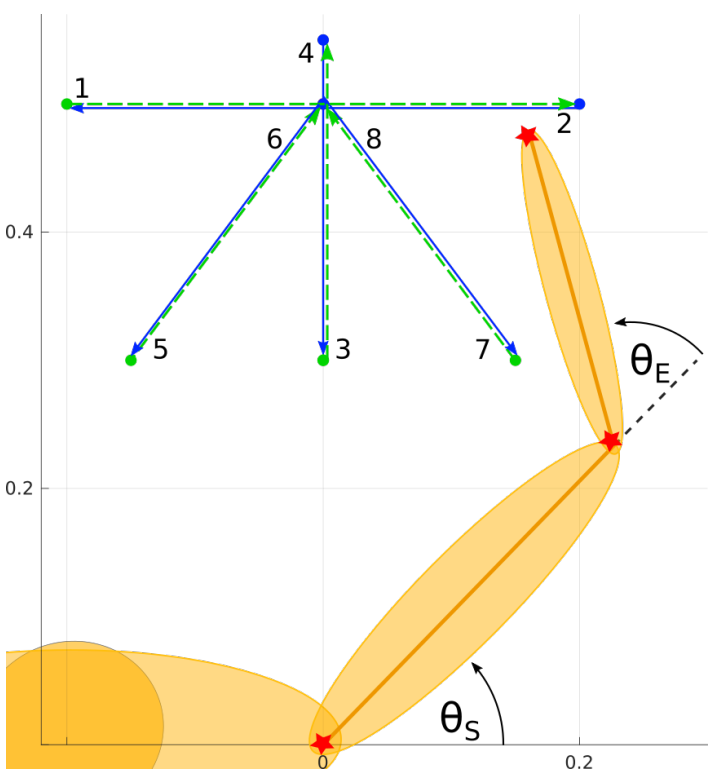
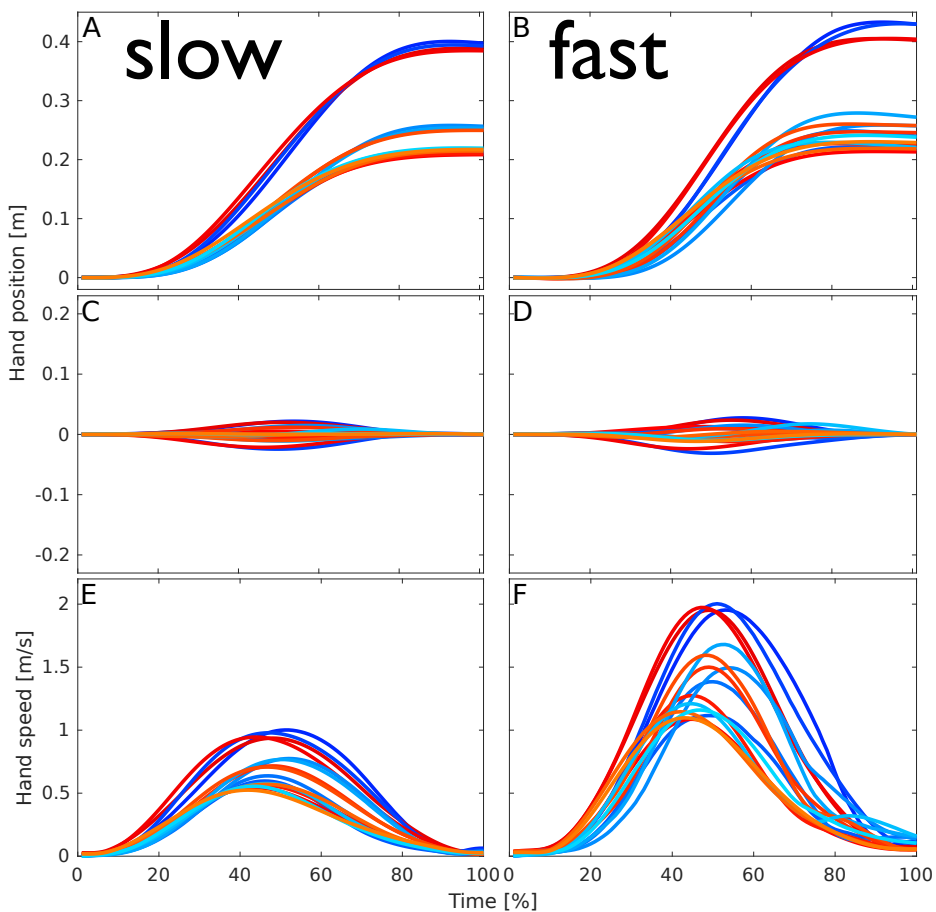
reflex loops
muscles biomechanics
control

Experiment in classical paradigm

"hand in space" level of description



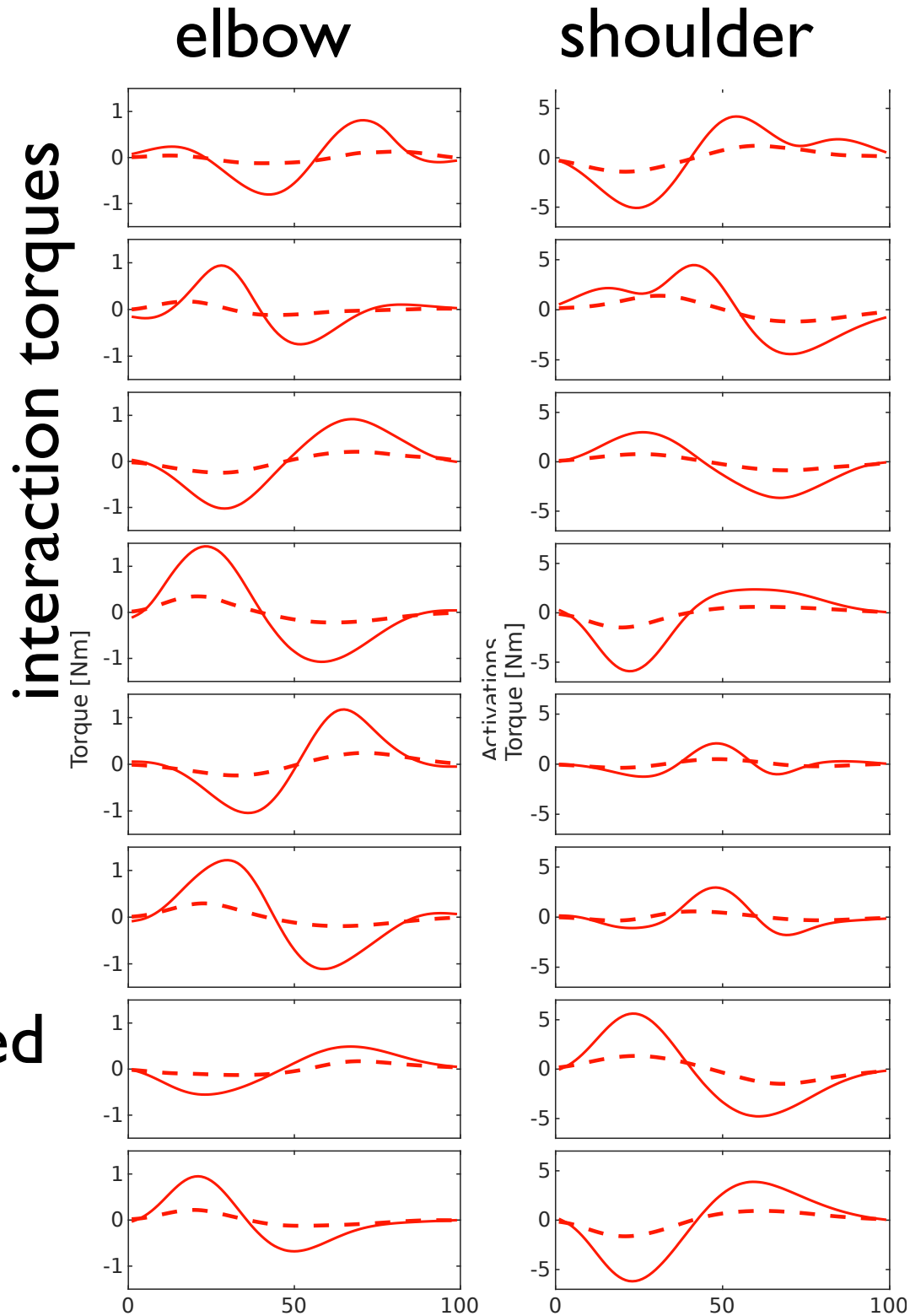




[Hummert, Zhang, Schöner, submitted]

Experiment in classical paradigm

joint/muscle
level of description



slow: dashed

fast: solid

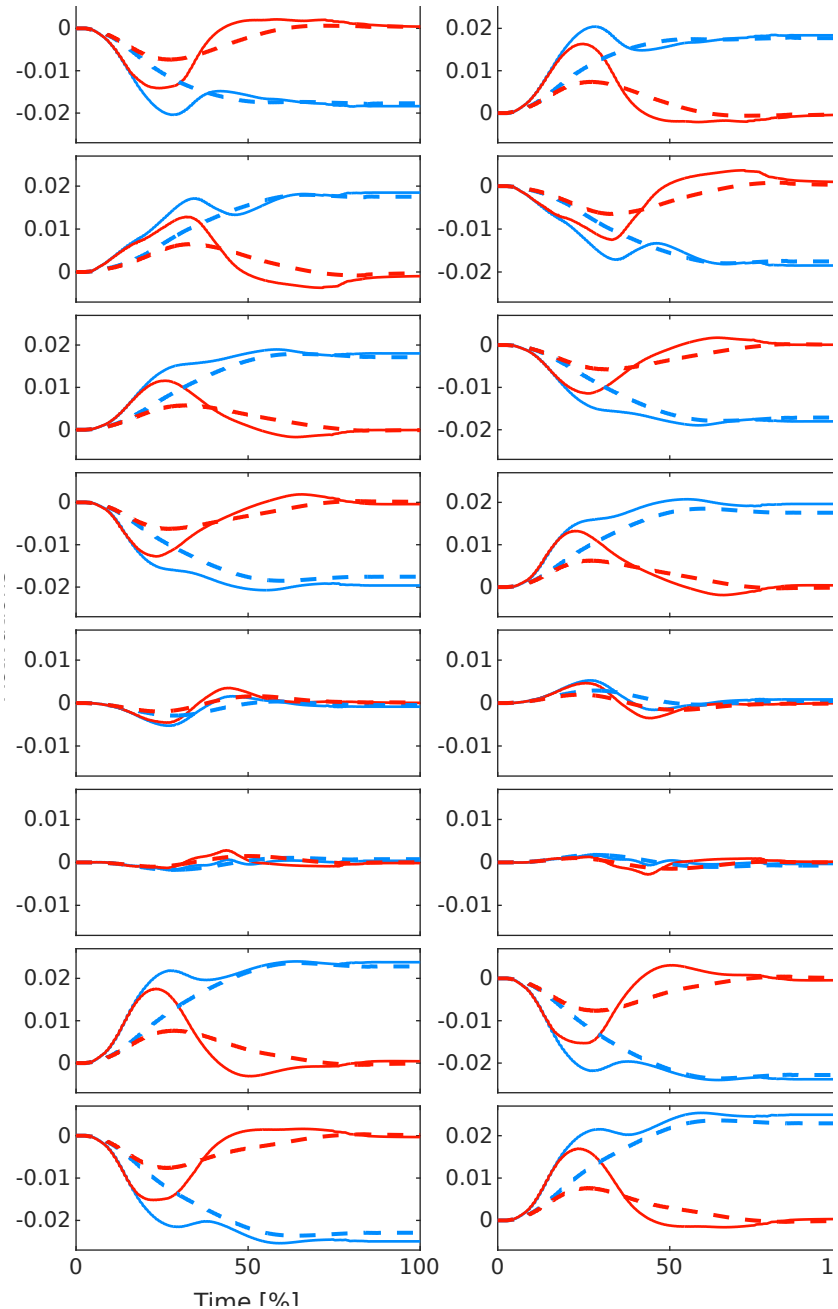
[Hummert, Zhang, Schöner, submitted]

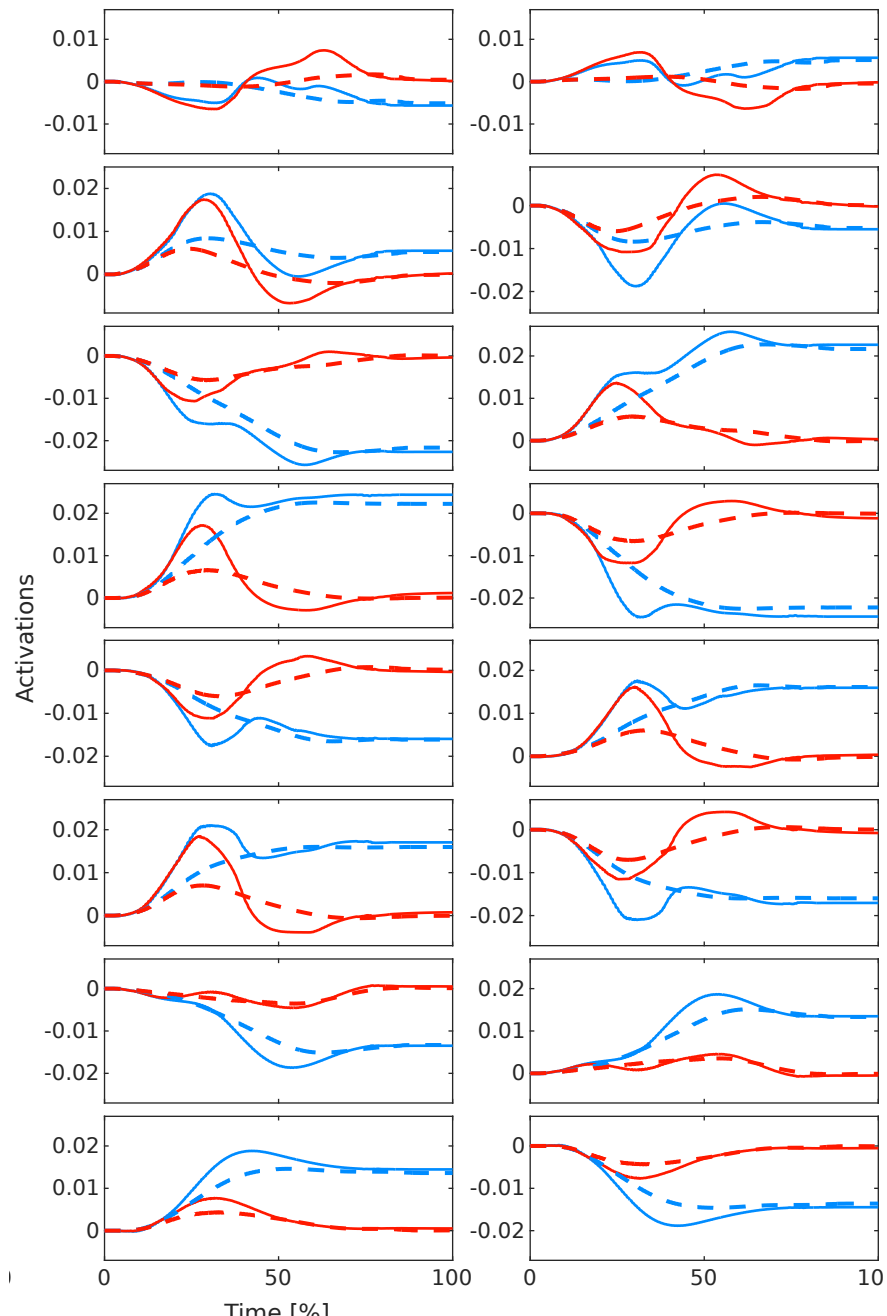
Implications

- kinematics invariant in space (=scales with speed)
- kinetics (biomechanical dynamics) not invariant
- => kinematic regularity is an “achievement”

Muscle activation red (ignore blue)

elbow flexor extensor shoulder flexor extensor



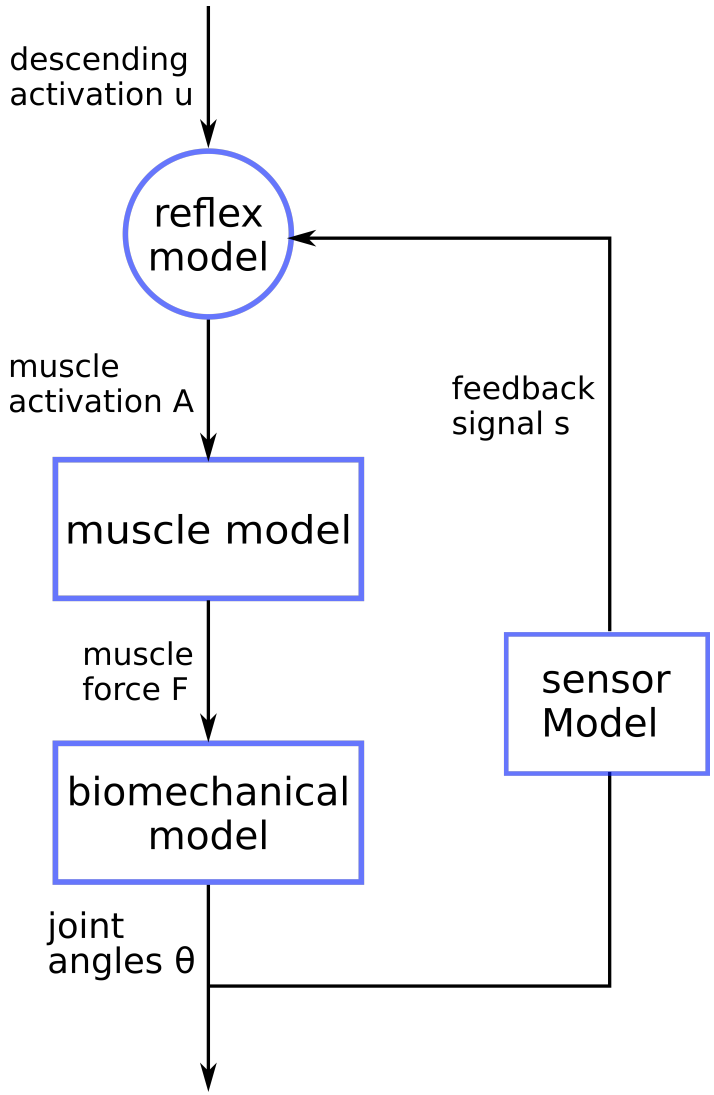


Muscle activation patterns

- are not invariant across movements
- not invariant across speed

Reflexes are critical

- the core idea of the Feldman/Latash school of thought:
- muscle activations are not "computed" from the timing signals…
- but emerge both descending activation and feedback signals

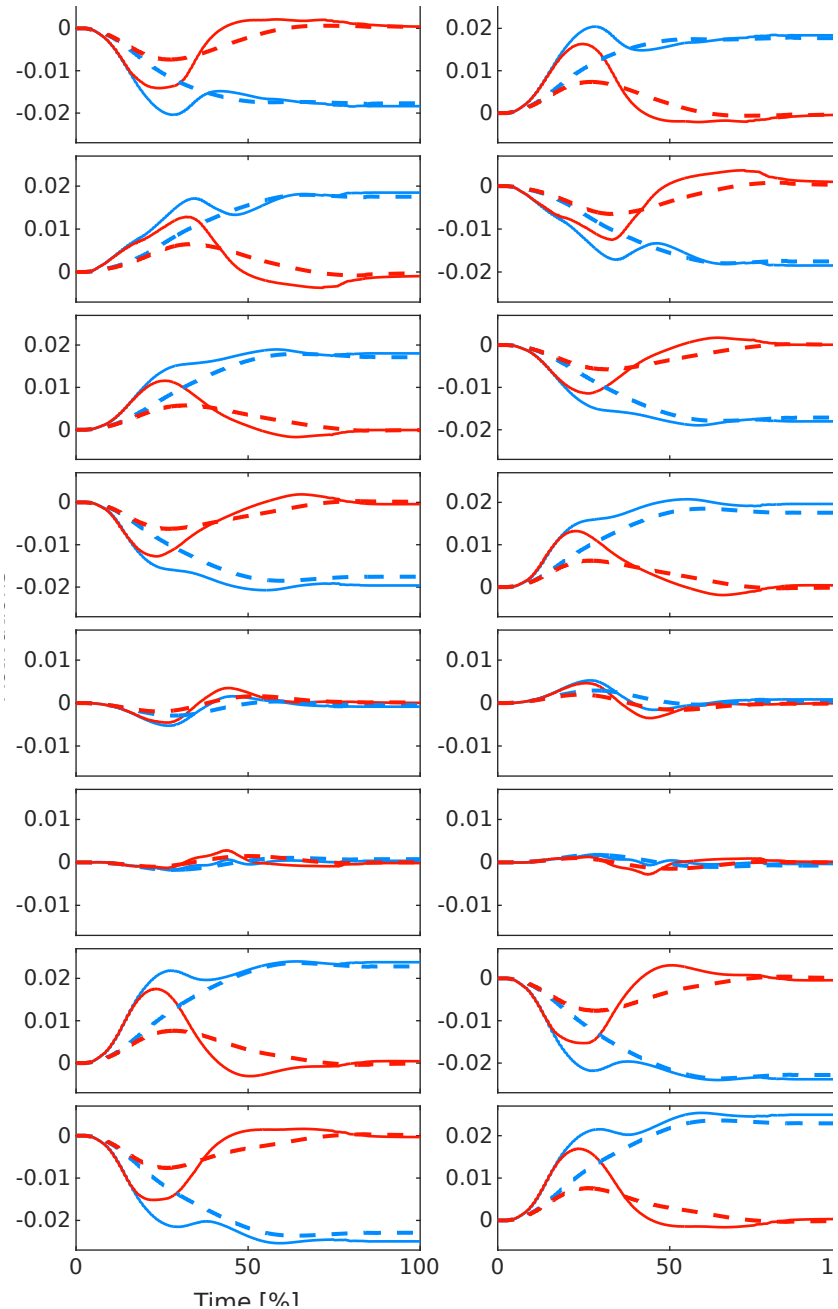


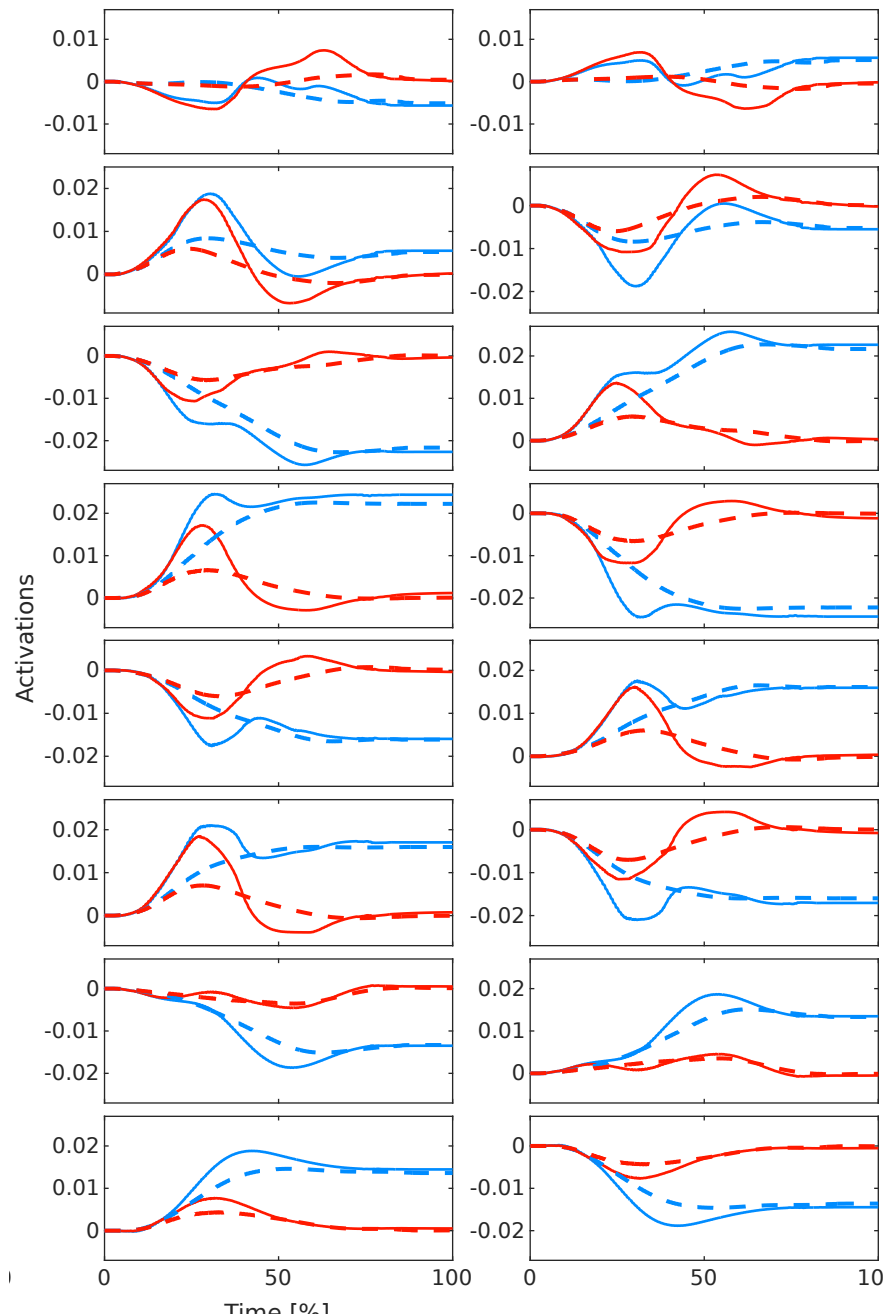
[Hummert, Zhang, Schöner, submitted]
Estimate descending activation by inverting model

Descending activation

blue

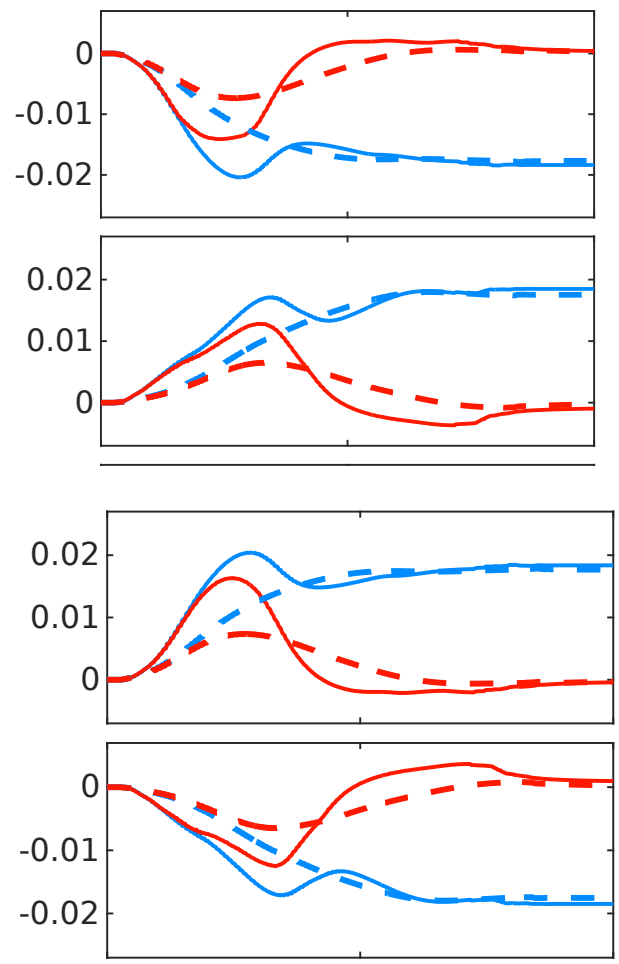
elbow flexor extensor shoulder flexor extensor





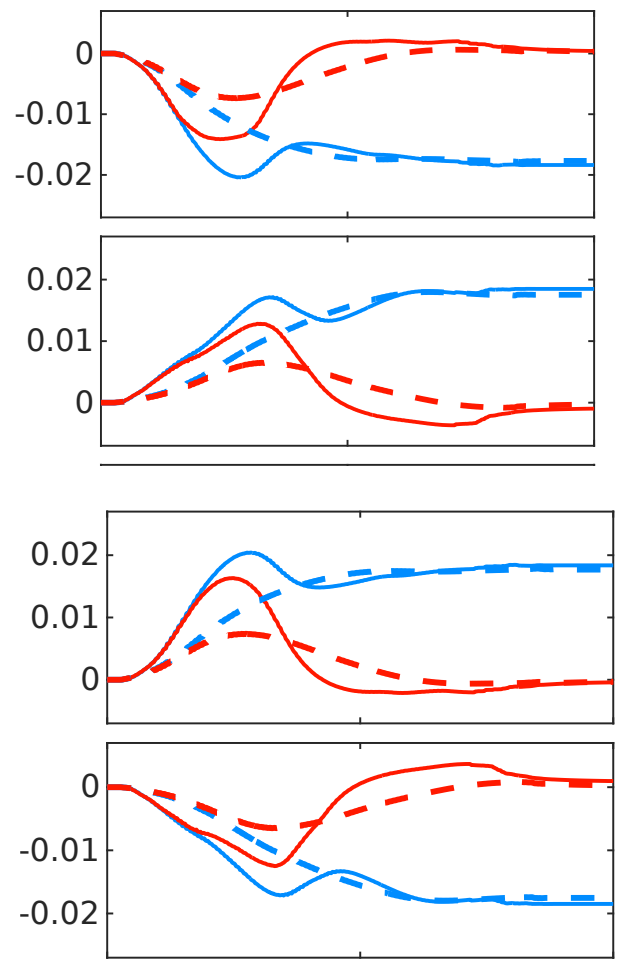
Descending activation patterns

- are qualitatively different from muscle activation patterns
- 1) do not return to initial level: to solve the Posture-Movement problem (Feldman, Latash)
- 2) deviate early in movement: reflex contributes substantially during movement

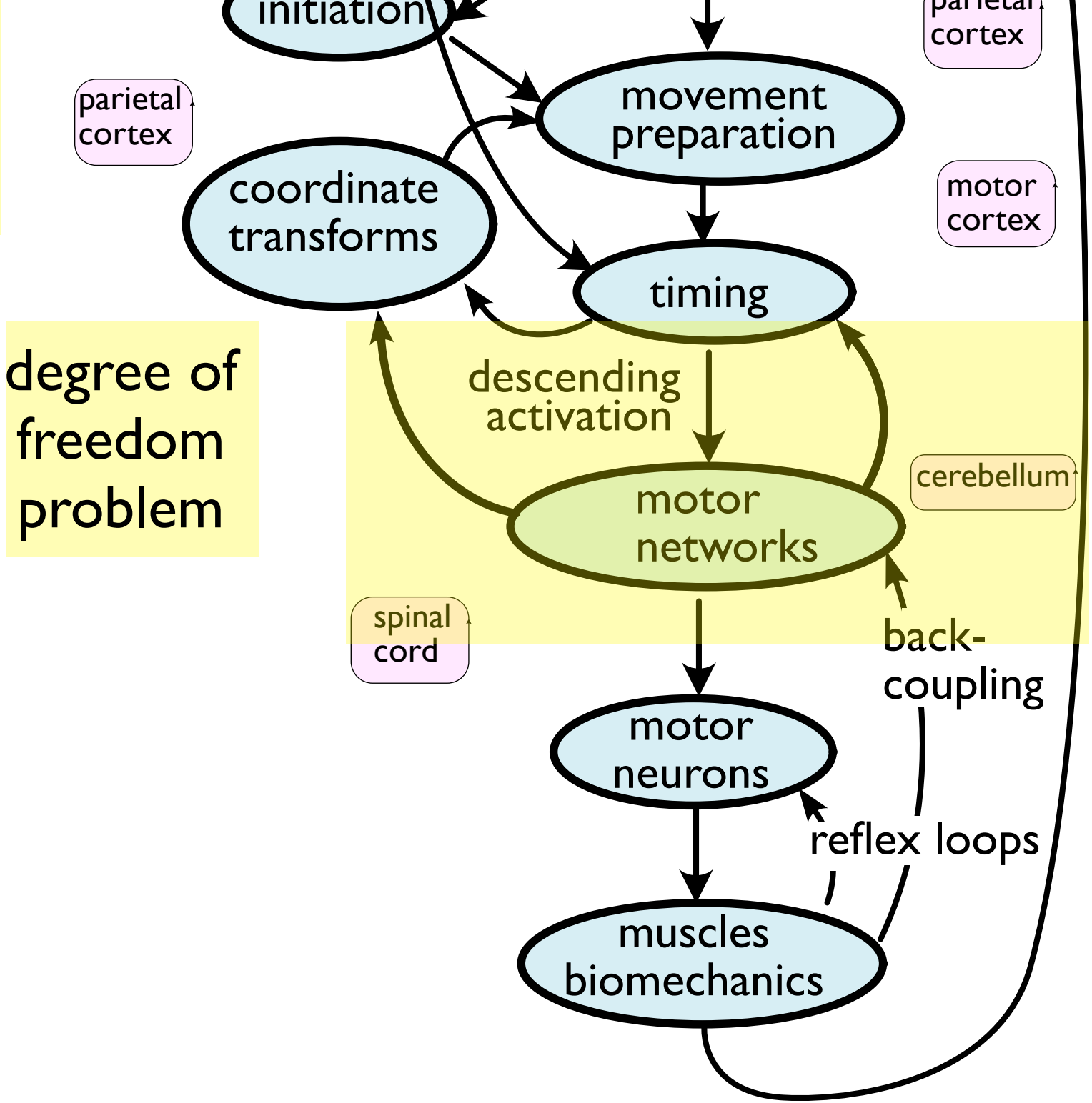


Descending activation patterns

- are “ramp-like” for slow movements
- with additional time structure overlaid over ramp for fast movements



DoF problem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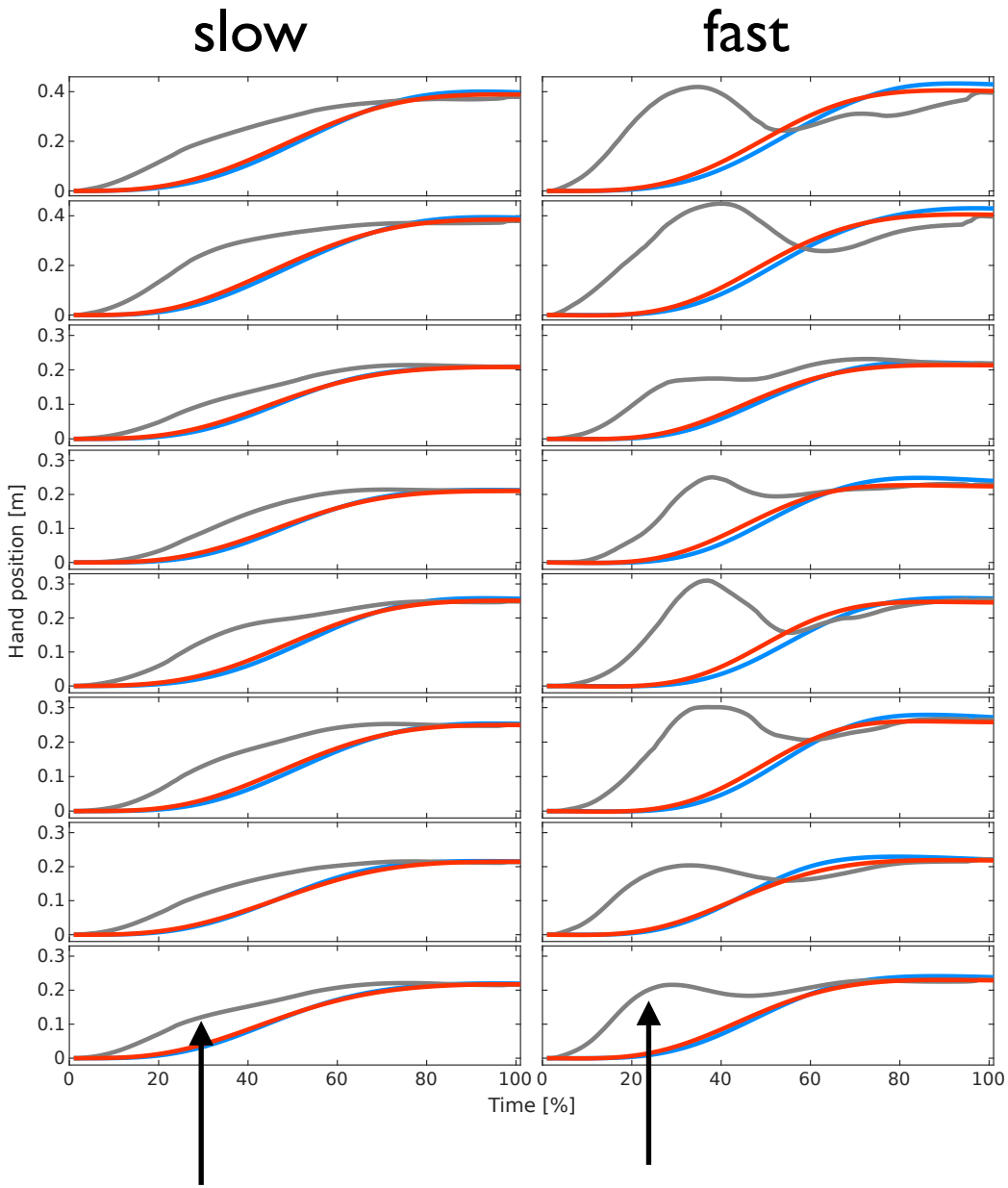
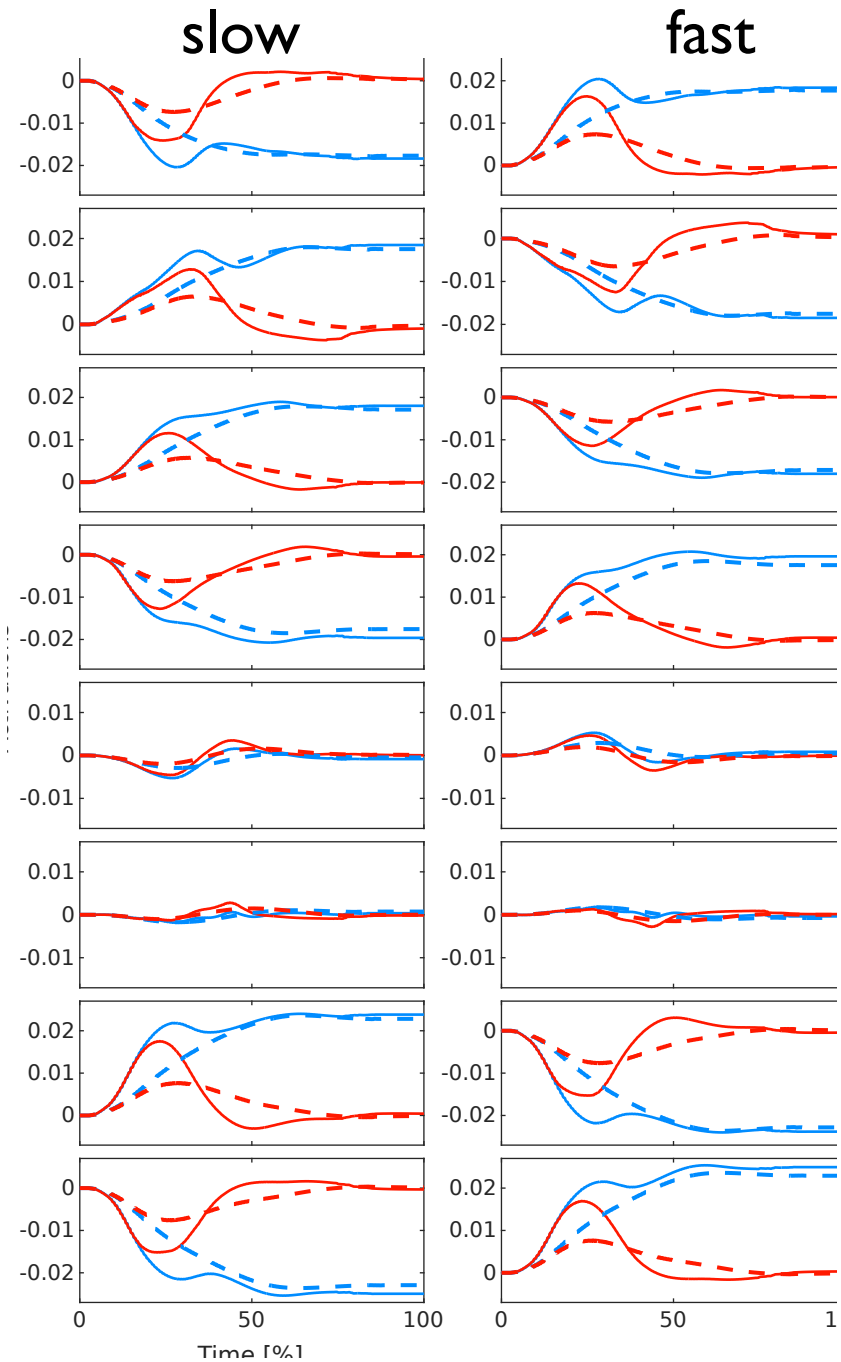
reflex loops
muscles biomechanics

DoF problem: Hand space vs. muscle space

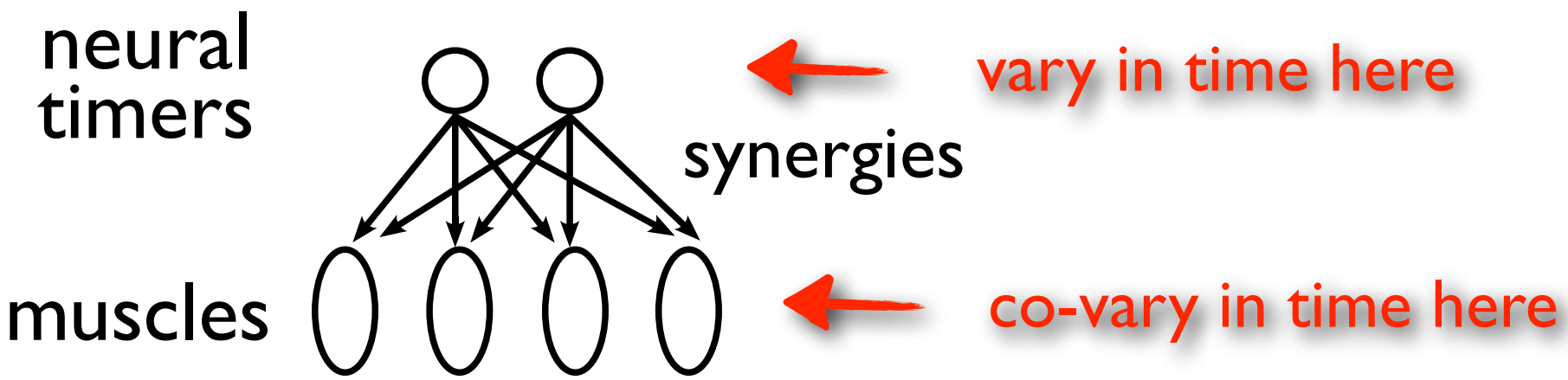


descending activation in hand space (grey)

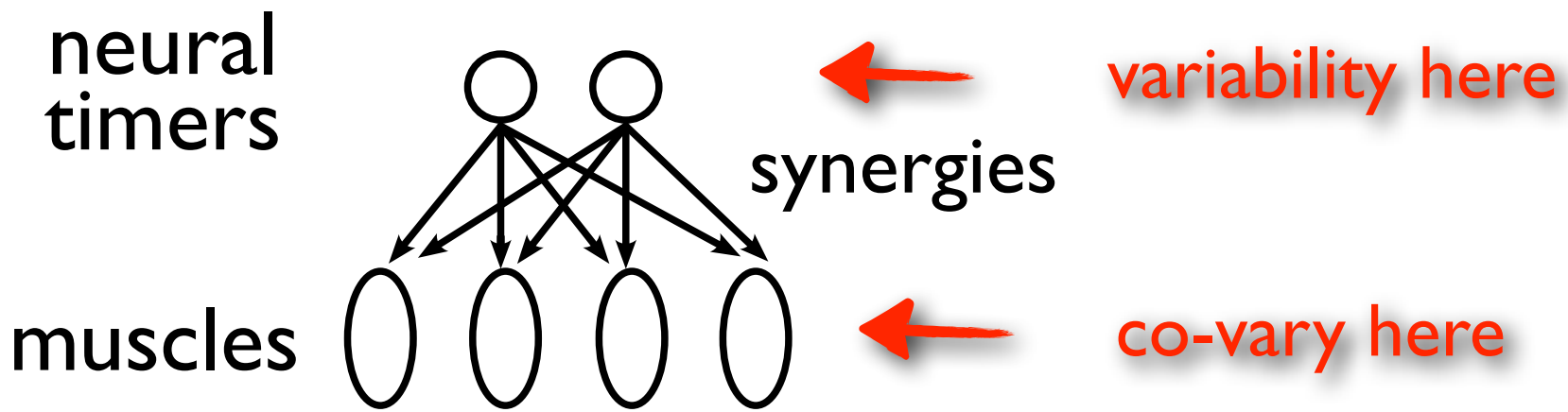


Classical synergy

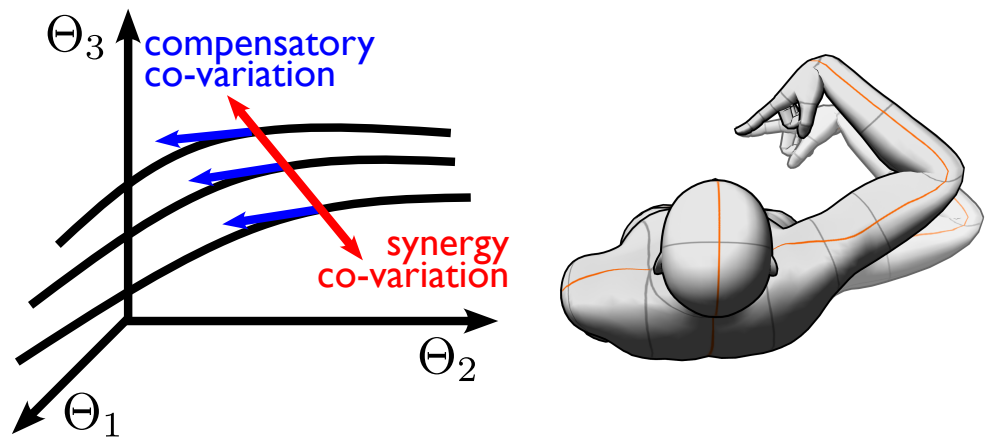
- to account for observed dimensionality reduction at the muscle/joint level…
- observed across time/movements



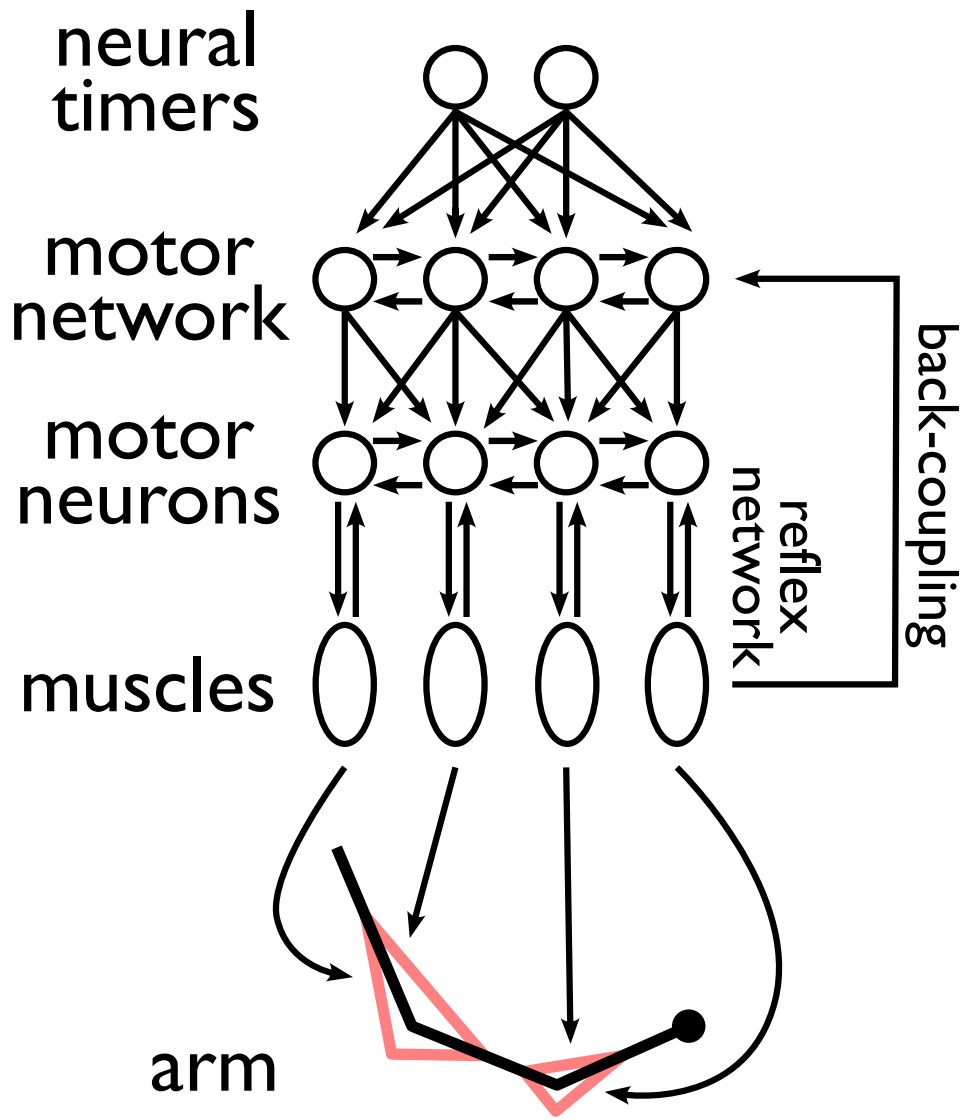
Classical synergy makes the wrong prediction for variability



- UCM effects show the opposite pattern of co-variation

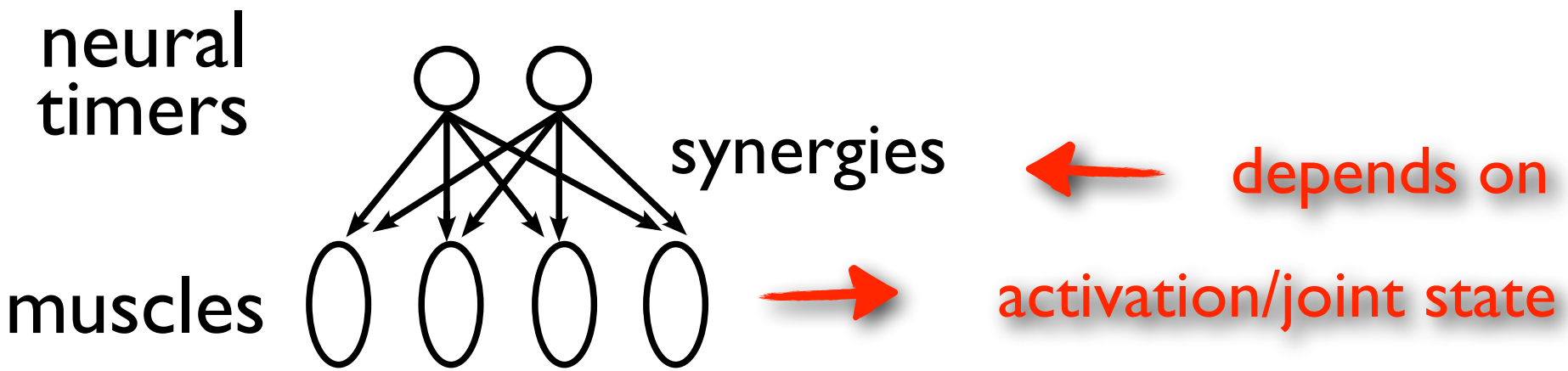


Solution: loopy neural map

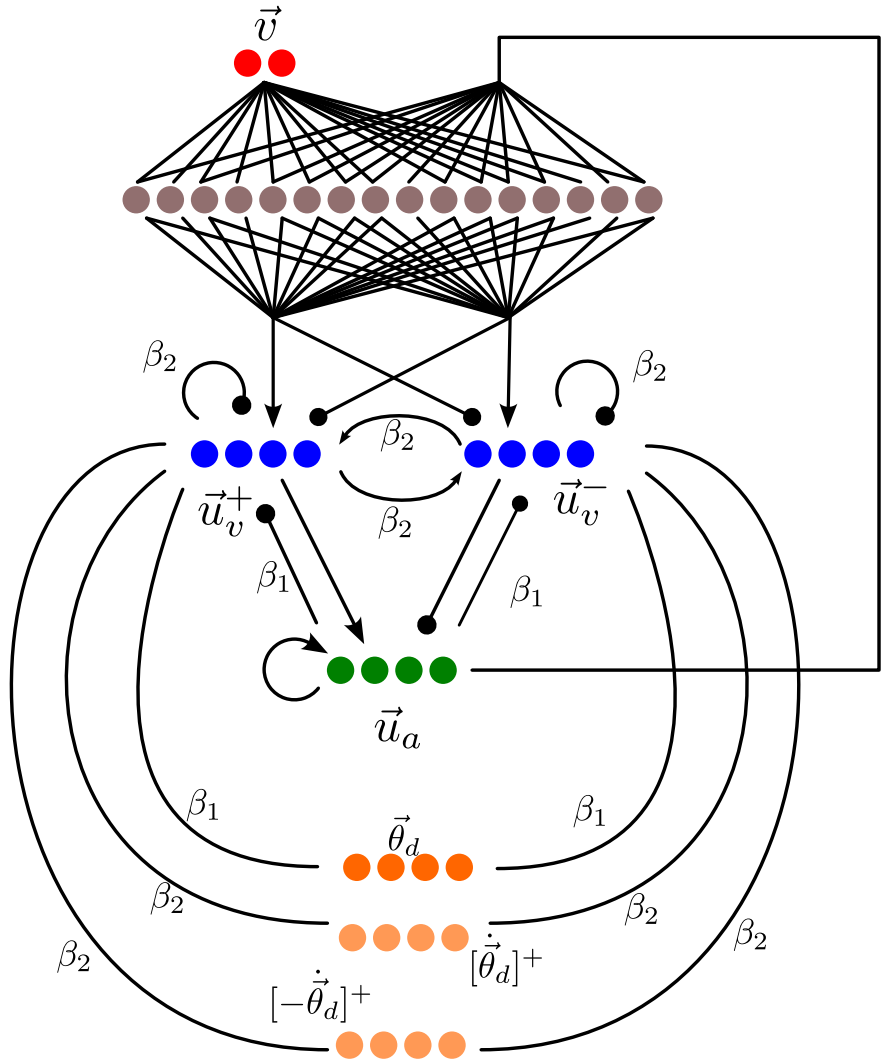


[Martin, Scholz, Schöner, 2009; Martin, Reimann, Schöner, 2019]

Forward map depends on the current joint/muscle configuration



Solution: an even loopier neural map



[work in progress Lukas Bildheim, GS]

Conclusion

- a neural architecture of movement generation
- visual cognition front end of DFT with online updating
- selection/detection decisions
- coordinate transforms
- neural oscillators with sequence generation transform to rate code..
- neural dynamic loops and reflexes