Sensory-motor control intro
Day 2
CoSMo 2015
Gunnar Blohm
Outline

- CoSMo organization (Gunnar) – Day 1 30 min
- Introduction to sensory-motor control 1
  - The computational neuroanatomy of sensory-motor control (Gunnar) 20 min
  - The anatomy of computation (Konrad) 30 min
    - Link back to neuroanatomy – discuss different types of modelling (Marr etc + data analysis)
- One computational way: Bayesian 100 min
  - Sensory: cue combination (Konrad)
  - Sensory-motor: decision making (Paul)
  - Motor: Kalman filter & online control (Konrad)
- Bayesian decoding PM tutorial (normative modelling & data analysis)
- How to model (Gunnar, Konrad & Paul) 5pm

- Introduction to sensory-motor control 2
  - Rewind: orthogonal axes to first day (computational approach): systems in the brain (Konrad) 30min
  - Many sensory-motor systems in the brain (Paul) 30min
  - Eye movement example (Gunnar) 45min
    - Sensory processes underlying eye movements
    - Sensory-motor for eye movements
    - Eye motor control
  - Linear systems theory (John) 90min
- Saccade model PM tutorial (John)
- How to write papers (Konrad) 5pm
Computational vs. systems approach

Konrad Körding
Many sensory-motor systems

Paul Schrater

(Reach & grasp mechanism: Hans Scherberger & Pieter Medendorp – July 8)
Eye movement systems example
Ocular orienting responses

- Eye, head, body
  - Linkages = dependencies, hierarchies
    - Rigid bodies connected at joints
  - Multiple degrees of freedom
    - Kinematic redundancy
      - Kinematic: study of properties of motion, i.e. position, velocity, acceleration, etc
      - Vs. dynamics: study of the rules governing the interactions of objects
  - Different properties
    - Inertia (due to mass)
      - Physical resistance to change of motion
    - Viscosity (muscles & soft tissue)
      - Resistance to deformation
    - Elasticity (muscles)
      - Tendency to return to original shape
Ocular orienting responses

- Eye, head, body
- Different oculomotor systems
  - Saccades
  - Pursuit
  - VOR, OKN
  - Vergence

Yarbus, 1967

Blohm, et al., 2003
Ocular orienting responses

- Eye, head, body
- Different oculomotor systems
- Pupil orienting
Target selection and decision making are integral part of motor planning and execution!

Cisek, 2007
Eye movement systems example

Sensory processing
Sensory processing

- Complex visual scenes
  - Attention
The brain’s approach

- Selective attention – interaction between
  - Bottom-up (determined by the brain’s processing capabilities)
  - Top-down (voluntary)
- Goal: further process only what might be of importance
- Decide & act?

- Attention, target selection & decision making processes interact with/are part of almost ALL sensory-motor processes
  - But they are often ignored, especially by the motor control community…
Current theories

- Attention

Itti et al., 1998

Tsotsos, et al. 1990
Eye movement systems example

Sensory-to-Motor transformations
Working memory

- Retain important information for immediate action
  - Relies on persistent mnemonic activity through a balance of local excitation and global inhibition

Lim & Goldman (2013)
Sensory-motor transformations

- **Reference frames**
  - Determined by sensory and motor apparatus
    - Vision: attached to the retina
    - Audition: attached to the head
    - Proprioception: relative joint angles
    - Arm movement: relative to attachment at shoulder
Sensory-motor transformations

- Reference frames
  - Knowledge about reference frames is required to localize sensory and motor events
    - Same retinal image – different spatial locations
Coding information in the brain

- **Receptive fields**
  - = activation pattern of a neuron for targets across space
  - We assume that the brain explicitly “codes” certain information
  - AND that we can decode it!

Blohm, Khan, Crawford, 2009 (adapted from Andersen, et al., 1985)
Gain modulation

- change of receptive field strength with secondary input

E.g. eye position gain modulation of visual receptive fields in posterior parietal cortex

Blohm, Khan, Crawford, 2009 (adapted from Andersen, et al., 1985)
Gain modulation

- Reference frame transformations
  - Zipser & Andersen, Nature 1988

Eye position gain modulation of hidden layer units
Gain modulation

- Powerful computational means for
  - Cue combination
  - Reference frame transformations
  - Multi-sensory integration...

Gain field theory

Constant receptive fields with gain modulation

Shifting receptive fields (deg)

Blohm & Crawford, 2009
Multi-sensory integration

Churchland (2011)
Bayesian computations in population codes

- Representing uncertainty with population codes
  - Probabilistic population codes
    - Poisson-like neural noise
    - Variance inversely related to gains of population code

Ma et al. (2006)
Neuronal implementation?

- Divisive normalization & marginalization
  - Relevant for sensory processing, visual search, object recognition, multi-sensory integration, coordinate transformations, navigation, inference, motor control, etc…

Ohshiro, Angelaki, DeAngelis (2011)
Problems with explicit divisive normalization

- The curse of dimensionality
  - $N^{(ds)}$ neurons needed (if using Pouget’s PPC)
    - $N$: neurons along each dimension
    - $d$: # dimensions
    - $s$: # signals to be combined
  - Example: $N=100$, $d=3$, $s=2 \rightarrow 10^{12}$ neurons needed!

- Network connectivity constraints
  - Huge connectivity - # connections for each neuron > # neurons
  - Precise structure required – extraordinary regularity

- Representation of population coding
  - All input and output codes must be the same (Weak Fusion Model)
  - Mixture of different codes is not trivial

- Alignment of population codes
  - Perfect alignment of codes required
A possible alternative: implicit approximate normalization (IAN)

- In machine learning, marginalization is known as the \textit{partition function problem}.
- Explicit partition functions are typically impossible to compute, but non-probabilistic approaches allow for solutions.

Standage, Lillicrap, Blohm (in preparation)
Choice & decisions

- Competition of alternatives
- Example 2: areas LIP / FEF

Schall, 2001
Current theories

- **Target selection**
  - Through the interaction of bottom-up and top-down attention

- **Decision making**
  - Different versions of rise-to-threshold models

Bogacz, 2007
Current theories

- **Target selection**
  - Through the interaction of bottom-up and top-down attention

- **Decision making**
  - Different versions of rise-to-threshold models

- **Computational principles at work?**
  - Competitive processing
  - Divisive normalization
  - Gain modulation
Diffusion models

- Example: left-right decisions
  - Integrated decision model (Mazurek, et al. 2003)
Eye movement systems example

Motor control & learning

(John van Opstal & Stefan Glasauer – July 2)
Eye/head plants

Eye and neck muscles

- Superior and inferior recti
- Medial and lateral recti
- Superior and inferior obliques

Blohm 2004

Lateral Neck Muscles
- Splenius muscle
- Levator scapulae muscle
- Sterno cleidomastoid muscle
- Scalene muscles
  - Anterior
  - Middle
  - Posterior
- Trapezius muscle
- Deltoid muscle
- Thyrohyoid muscle
- Omohyoid muscle (superior)
- Omohyoid muscle (inferior)

Medical-look.com
Eye/heads plants

- Eye and neck muscles properties
  - Damped spring-mass system equivalent

Equation of motion of eye ball:

$$J \cdot \frac{d^2 \theta}{dt^2} + F_p = F_m$$

Muscle force applied:

$$F_m = F_0 - R_m \cdot \frac{d\theta}{dt} - \frac{R_m}{K_{se}} \cdot \frac{dF_m}{dt}$$

Passive muscle/tissue force:

$$F_p = \frac{R_1 R_2 \cdot \frac{d^2 \theta}{dt^2} + (R_1 K_2 + R_2 K_1) \cdot \frac{d\theta}{dt} + K_1 K_2 \cdot \theta - (R_1 + R_2) \cdot \frac{dF_p}{dt}}{(K_1 + K_2)}$$

Robinson (1964), Scudder (2009)

$J$: moment of inertia
$F_p$: passive force (muscle tissue)
$F_m$: active muscle force
Eye/head plants

- **Eye and neck muscles properties**
  - Damped spring-mass system equivalent
    - $4^{th}$ order differential equation
    - Overdamped system (no oscillations)
    - Solution to static $F_0$: Exponential behavior with 2 time constants
      - Fast: plant inertia
      - Slow: plan viscoelasticity
  - Higher-order models possible
  - Much more detail here: Quaia, Optican, et al. (2009a,b, 2010)

Robinson (1964), Scudder (2009)

$J$: moment of inertia
$F_p$: passive force (muscle tissue)
$F_m$: active muscle force
Gaze holding: the neural integrator

- How do we get the tonic portion?
  - Neural integrator

Leigh & Zee 2006
Oculomotor control structures

Saccades

Krauzlis, 2004
Oculomotor control structures

- Motor circuitry of saccades

Shaikh, Miura, Optican, Ramat, Leigh, Zee (2007)
Classical control

- Vestibulo-ocular reflex

- Angular velocity from semi-circular canals: \( \omega \)
- Linear acceleration senses by otolith organs: \( \alpha \)
- VO: vestibular-only neurons
- EM: eye movement sensitive neurons

Green & Angelaki 2004
Optimal feedback control

- **Saccadic adaptation**
  - Based on “prediction error”
  - Optimal control penalizes a cost, e.g. energy, error, time

Chen-Harris, Joiner, Ethier, Zee, Shadmehr (2008)
Mathematical formulation of OFC

Sensory state of our body and the world we interact with:

\[ x^{(k+1)} = Ax^{(k)} + Cu^{(k)} + \varepsilon_u \]

motor command

What we can observe about the state:

\[ y^{(k)} = Bx^{(k)} + \varepsilon_y \]

sensory noise

Cost to minimize:

\[ J = \sum_{k=0}^{p-1} u^{(k)T} L(k) u^{(k)} + y^{(k+1)T} T^{(k+1)} y^{(k+1)} \]

Feedback control policy:

\[ u^{(k)} = G^{(k)} \hat{x}^{(k)} \]

Belief about state:

\[ \hat{x}^{(k+1)} = \hat{A}\hat{x}^{(k)} + \hat{AK}^{(k)} \left( y^{(k)} - \hat{y}^{(k)} \right) + \hat{Cu}^{(k)} \]

Predicted sensory consequences

Measured sensory consequences
Stochastic control

- Smooth pursuit
  - Stochastic pursuit model

Orban de Xivry, Coppe, Blohm, Lefevre 2013
Neural Networks

- Smooth pursuit – saccades coordination

Grossberg, et al. (2012)
Hierarchical control

- Eye-head Saccades
  - Endpoint control
    - Vs. trajectory control
  - Head motion = perturbation to gaze goal

Daye, Optican, Blohm, Lefèvre (2014)
Motor planning & execution

- Closing the loop… sensory and motor processes are not independent!

Cisek, 2007
Sensory processing

- Consequences of 3D binocular eye movements

Blohm & Lefèvre (2010)

Blohm, et al. (2008)
Sensory processing

- Consequences of 3D binocular eye movements
- Eye/head movements orient attention to goal and suppress information from non-goal locations

Khan, Blohm, Pisella, Munoz (2015)
Linear systems theory

John van Opstal
That’s all folks!