Decision making in motor control

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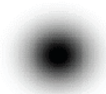
Where should you aim at when playing darts?

Motor uncertainty:

Motor errors

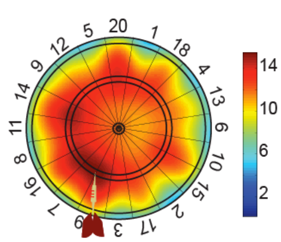


Deciding optimally

$$E\left[Utility(decision)\right] = \sum_{\substack{possible\\outcomes}} p(outcome \mid decision)\, U(outcome)$$

$$best\ decision := \arg\max_{\substack{possible\\decisions}} \left(E\left[Utility(decision)\right]\right)$$

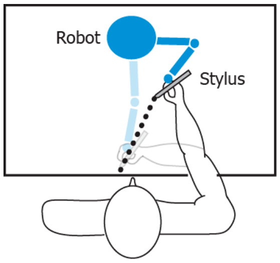
Expected reward:



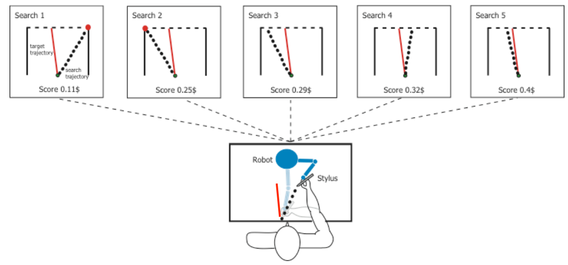
Sequential decision making Exploration/ Exploitation

Greg Dam

Simple motor search



Experimental Paradigm



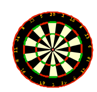
People get money for best search, unimodal rewards

What is optimized in real movements?

- Typically not $$

- Nearness to target
- Time and magnitude forces
- Whole movement

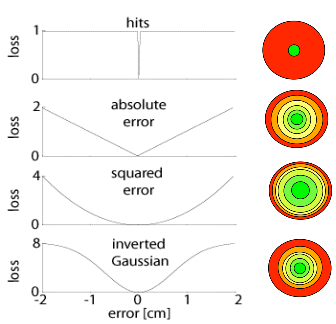
Moving to a target



Measure internal dartboard

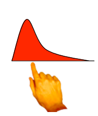
Distance to target must relate to utility

Loss functions for errors

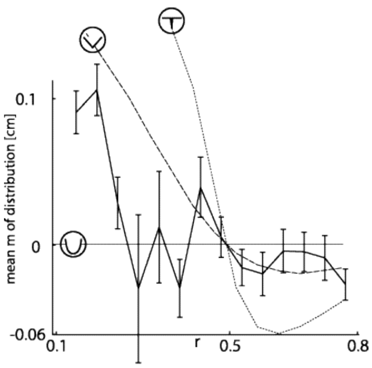


This is the standard

Experimental Design: shooting peas



Models and Single subject data



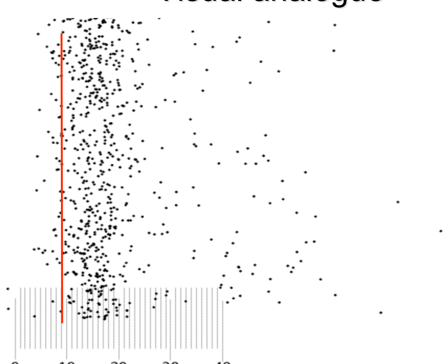
All subjects, smoothest loss function that explains data

$$F(\Psi)=\sum_{i=1}^{14}\left(m_i-\hat{m}_i(\Psi)\right)^2+S\sum\left(\frac{d^3\Psi}{dx^3}\right)^2$$

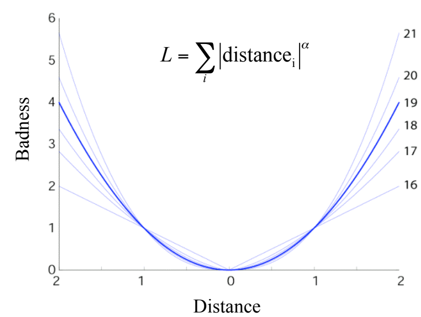
Robust Fitting

Kording & Wolpert, PNAS 2004, link to Angela Yu's talk

Visual analogue



Loss function

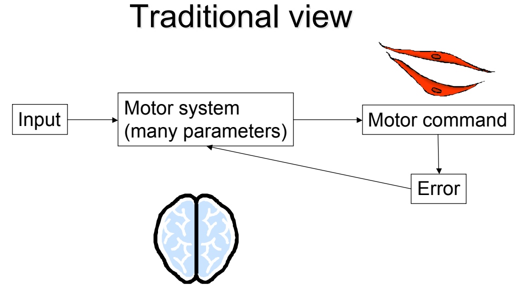


Relation to causal inference

To optimize, small movement variance is necessary

- Muscles change over time
- -> Motor adaptation

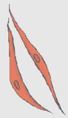
Traditional view



System only adapted when an error is made

Timescales and credit assignment

Muscle properties



Many timescales
Fatigue, Nutrients, Training, Disease e.t.c.

Hard to observe

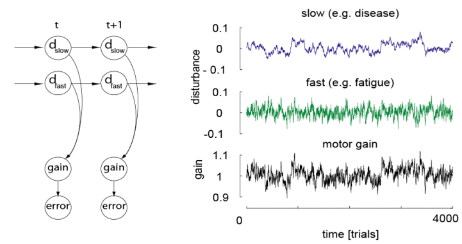
Motor gain

Actual movement

observed

Adaptation=Inference

Generative model



Bayesian inference:

Each random walk: $disturbance_\tau(t+1) = (1-1/\tau)disturbance_\tau(t) + w_\tau(t)$

Process noise: $w_\tau(t)$ is drawn from: $N(0, c/\tau)$ parameter

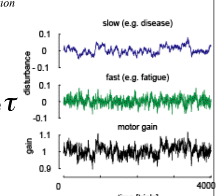
Overall motor gain: $gain(t) = 1 + \sum_\tau disturbance_\tau(t)$

Observation: $z = gain(t) + v_{observation}$

Kalman Filter

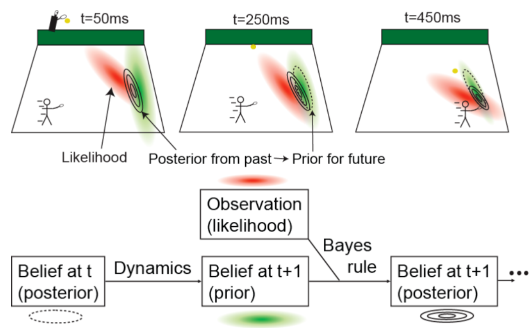
State: *disturbance* at each time scale τ

$S_{t+1} = MS_t + K(gain\ error)$

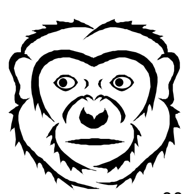


See also Kronenberg & Ghahramani 2002

How does such a Kalman Filter work?



Saccadic target jump experiments



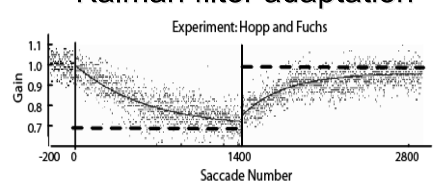
30%

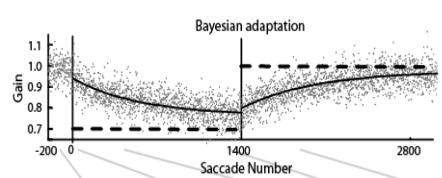
Eye X
Target ● ● ●

Equivalent to muscles being too strong

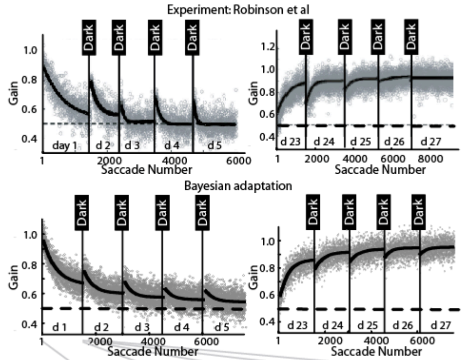
McLaughlin 1967

Kalman filter adaptation

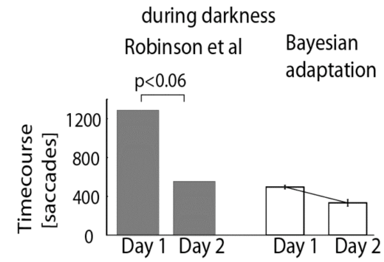




Several days

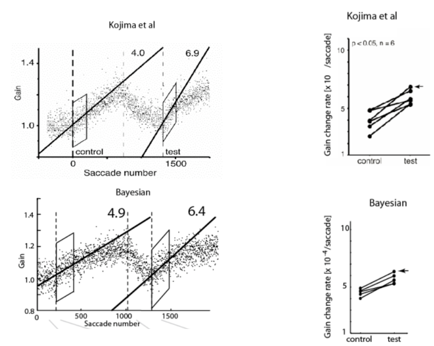


More uncertainty leads to faster learning

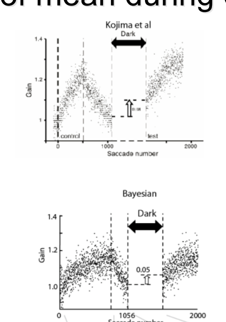


More uncertainty – faster learning

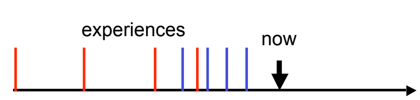
Double reversal



Change of mean during darkness



Very general problem



what does the past mean about now?

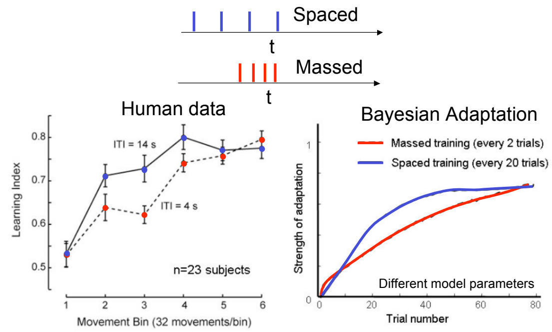
Learning and memory: summarizing past

Forgetting: Information becoming useless

Adaptation: Multiple timescales of learning and forgetting

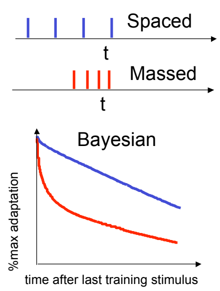
Human force field paradigm

Massed versus spaced training

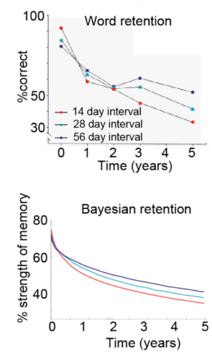


Courtesy Vincent Huang, Shadmehr lab

Prediction: Decay over time



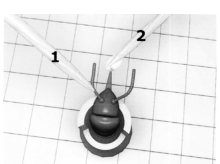
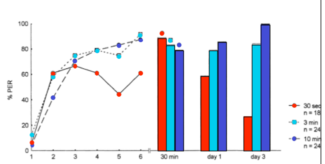
Vocabulary learning



Bahrick, Bahrick
Bahrick &Bahrick 93

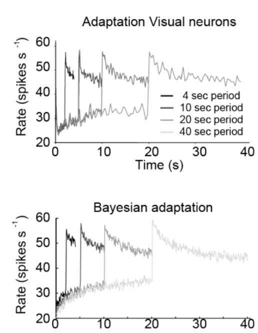
Same effect in honeybees

Conditioning of proboscis extension reflex

Giurfa & Malun, 2004 ,Menzel et al., 2001

Visual adaptation



Fairhall et al 2002

Adaptation as Inference

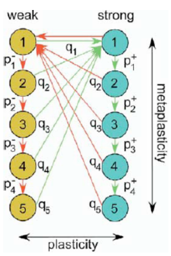
- Korenberg & Ghahramani 2002: Bayesian Adaptation on 1 timescale
- Krakauer & Shadmehr
- Reinforcement learning: Yu & Dayan
- Ernst & colleagues
- McLaughlin 1967

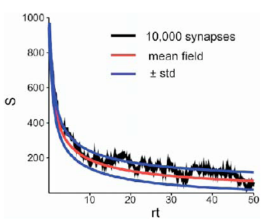
Multiple timescales

- Newell 1991
- Hinton Neural Networks
- Smith and Shadmehr
- Krakauer
- Anderson / Psychology community

Potential neural implementation

- Fusi et al 2005: Interesting multiscale behavior of synapses



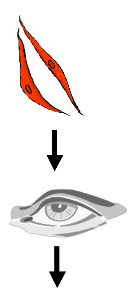


Other normative models

- Neural coding (Olshausen, Lewicki, Kording, …)
- Anatomy (Chklovskii, …)
- Reinforcement Learning (Dayan, Niv, …)
- Classical Conditioning (Daw, …)
- Psychology (Tenenbaum, Chater,…

Conclusion

Normative Ideas



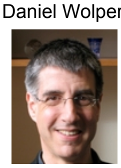
Error

Next lecture, more interesting causes for errors, structural uncertainty

Acknowledgements

Josh Tenenbaum

Daniel Wolpert



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