Relationship between Flash-Lag Effect and Delay Compensation in the Nervous System

Cognoscenti Talk
February 19, 2006
Yoonsuck Choe
Department of Computer Science, Texas A&M University
Joint work with Heejin Lim

Whence Prediction?
Thorpe and Fabre-Thorpe (2001)
• Due to neural conduction delay (couple of 100 ms), we cannot even seem to catch up with the present.
• At best, we will be predicting the present, based on the past.

Strange Perceptual Illusion: Flash Lag Effect

Physical Perceived
• Moving object seems to be ahead of an aligned, flashed object (Nijhawan 1994).
• Numerous variations: orientation, luminance, etc.

Demo: Flash Lag Effect
Implications of FLE

• There may be mechanisms in the brain for delay compensation through extrapolation.

• The brain may predict the present, based on the past.

• Alternative hypotheses: differential latency (Whitney and Murakami 1998), postdiction (Eagleman and Sejnowski 2000), etc.

With Delay Compensation: FLE

W/O Delay Compensation: No FLE

Research Questions

• How can the nervous system compensate for internal delay?

• Are there single-neuron-level mechanisms for that?
### Potential Answers

**Extrapolation** can be used to compensate for delay:

- That can happen at a single-neuron level.
- Facilitatory neural dynamics may be the underlying mechanism.
- FLE may be a side-effect of such a compensatory process.

### Approach

Integrate insights from:

1. Psychophysics: Flash-lag effect
2. Neurophysiology: Dynamic synapses
3. Computational theory: Extrapolation

And, potential link to neurology (autism and dyslexia).

---

**Dynamic Synapses**

The effect of synaptic transmission changes dynamically.

- Dynamic increase: Facilitating synapse.
- Dynamic decrease: Depressing synapse.
- Time scale: several hundred milliseconds from the onset (Liaw and Berger 1999; Fortune and Rose 2001; Markram 2002)

(Markram et al. 1998)
Alternative Role of Dynamic Synapses

• Previous: **memory** (sensitization and habituation) (Zucker 1989; Fisher et al. 1997).

• Previous: **temporal information processing** (Fuhrmann et al. 2002; Markram et al. 1998; Fortune and Rose 2001).

• Proposed: **extrapolation** (facilitating synapses).

Available Resource ($R$) and Synaptic Efficacy ($U$)

- $R$: Fraction of recovered neurotransmitters.
- $U$: Probability of neurotransmitter release.
- Postsynaptic response is dependent on $R$ and $U$.

Model: Dynamic Synapse

- Synaptic efficacy $U$ (Markram et al. 1998; Fuhrmann et al. 2002):

$$\frac{dU}{dt} = -\frac{U}{\tau_f} + C(1 - U)\delta(t - t_s),$$

where $\tau_f$: time constant for the decay of $U$; $C$ a constant determining the increase in $U$ due to spikes at $t_s$; and $\delta(\cdot)$ the Dirac delta function.

- To model extrapolation in the decreasing direction:

$$C = \text{sign}(I(n - 1) - I(n)) \left(\frac{I(n - 1)}{I(n)}\right) r,$$

where $I(n)$ is the inter-spike interval.

Target Experiment: Luminance FLE

- Works in both directions: increasing or decreasing.
- A single neuron can model the phenomenon.
  - Firing rate represents the perceived luminance.
Model: Membrane Potential

- Postsynaptic current $P(t)$:
  \[ P(t) = E e^{-\frac{t}{\tau_p}}, \]  
  \[ E = A U, \]  
  (3)
  (4)

- Membrane potential $V_m(t)$:
  \[ V_m(t) = V_m(t-1)e^{-\frac{t}{\tau_m}} + P(t)(1-e^{-\frac{t}{\tau_m}}). \]  
  (5)

- Once $V_m$ exceeds the spike threshold $\theta$, a spike is generated, followed by an absolute refractory period of $\tau_{\text{refrac}}$.

Luminance FLE: Summary

- FLE can be due to delay compensation mechanism.

- Facilitating synapses may be the neural basis of delay compensation.

- Limitations:
  - Cannot explain cross-neuronal facilitation such as orientation FLE

Target Experiment: Orientation FLE

- Cannot model with single neuron.
  - V1 orientation-tuned cells have narrow tuning.

- Need network of neurons, with directionally biased weights.
Model: A Ring of Orientation Cells

- Shift in firing rate distribution when FLE occurs.
- Needed:
  - Directionally biased connection weights.
  - Facilitating dynamics.

Model: STDP and Facil. Synapses

- Spike Timing Dependent Plasticity (Bi and Poo 1998): Set up directionally biased weights.
- Facilitating Synapses: Extrapolation across connections.

Results: Learned Weights

- Weight in the direction of rotation increases.
- Weight in the opposite direction of rotation decreases.

Results

- Peak firing neuron shifts in the direction of rotation.
Results: STDP or Facil. Synapse Alone

- STDP or facilitating synapses alone was insufficient.

Orientation FLE: Summary

For cross-neuronal facilitation, both
- STDP
- Facilitating synapses are needed.

Application: Pole Balancing

- 2D pole balancing problem.
- Delay introduced in input (position and pole angle).
Neuroevolution of Recurrent Neural Network Controller

- Fully recurrent neural network controller.

Approach: Add Dynamics to Neuron Activation

- Facilitatory activity (left):
  \[ A(t) = X(t) + (X(t) - A(t - 1))r, \]
  \( A(t) \): facilitated activation level at \( t \); \( X(t) \): instantaneous activation; \( r \): facilitation rate \((0 \leq r \leq 1)\).
- Decaying activity (right): \( A(t) = A(t - 1)r + X(t)(1 - r) \).

ESP Activation

- Neuron state is determined by instantaneous weighted sum of activity:
  \[ X_i(t) = g(\sum_{j \in N_i} w_{ij}X_j(t)), \]
  where \( g(\cdot) \) is a nonlinear activation function, \( N_i \) the set of neurons sending activation to neuron \( i \), and \( w_{ij} \) the connection weight from neuron \( j \) to neuron \( i \).

Encoding \( r \)

- ESP was modified to use the facilitating or decaying dynamics.
- The rate parameter \( r \) was encoded in the chromosome so that it can evolve.
**Experiment**

Compare task performance under three types of dynamics:

- **Control**: Basic ESP implementation.
- **FAN**: Facilitatory Activation Network.
- **DAN**: Decaying Activation Network.

**Results: Activation Pattern**

- Last 1000 steps in successful balancing trials.
- 1-step delay, from iteration 50 to 150.
- FAN shows smoother, low-amplitude oscillation.

**Results: Cart Trajectory**

- Last 1000 steps in successful balancing trials.
- 1-step delay, from iteration 50 to 150.
- FAN shows a smooth trajectory with a much smaller footprint.

**Results: Success Rate**

- Different delay conditions were tested.
- FAN showed best performance under all conditions (t-test, $p < 0.005$, $n = 250$).
**Results: Speed of Learning**

- Different delay conditions were tested (same as above).
- FAN showed best performance under all conditions (t-test, $p < 0.0002$, $n = 250$), except for the $\theta_z$-delay case ($p = 0.84$, i.e., no difference).

**Results: Effect of Increased Delay**

- Performance under increased delay and input blank-out period.
- In all conditions, FAN performed the best.

**Blank-Out as External Delay**

- Input feed cut off for $40 \sim 500$ ms while balancing a virtual pole.
- Humans are good at dealing with input blank-out.
- FAM shows similar robustness.

**Analysis: Evolution of $r$**

- FAN: best neurons had high $r$
- DAN: best neurons had low $r$
Summary: Pole Balancing

- Facilitatory dynamics help combat debilitating effects of noise in the input.
- Facilitatory dynamics can help in delay in external environment as well (potential for real prediction?).
- Decaying dynamics make things worse.

Discussion

- New role for facilitating synapses: extrapolation.
- Facilitation should happen both in the increasing and the decreasing directions.
- Novel prediction regarding facilitating synapses: equation 2.
- Ability to predict future arising from the need to predict the present?

Future Directions

Autism:
- Problem in coherent motion detection (Milne et al. 2002).
- Problem with processing moderately rapid motion (Gepner et al. 2001; Gepner 2002).

Dyslexia:
- Difficulty with processing rapidly changing stimulus (Hari and Renvall 2001)

Predictions:
- Autistics and dyslexics may not perceive FLE.
- Abnormal growth in brain size may outgrow built-in delay compensation mechanisms.

Conclusions

- Facilitatory (extrapolatory) dynamics at a single-neuron level can help compensate for neural delay.
- Facilitatory synapses may be implementing such a function: They are not just for memory!
- There may be possible connections to predictive mechanisms in the brain.
Reference


