

シミュレーションで読み解く生物の 複雑性

先進理工学専攻
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生物の特性

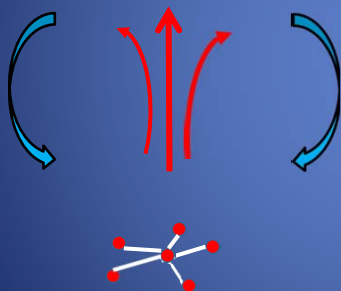
階層性:異なる時間と空間のスケール(DNA→
タンパク質→細胞→器官→器官系→個体
→個体群)

多様性:共生(熱帯雨林の植物分布、タンパク質の
機能、人間社会の行動)

複雑性:ネットワークシステム(細胞システム、脳、
運動制御、魚群など)

注目すべきこと

全体の秩序(巨視的)



局所的な相互作用

- 異なるスケールの階層構造
- 空間的スケール
- 時間的スケール
- 動的秩序の創発
- システムとしての機能

研究に関するキーワード

- 自己組織化・自己組織臨界現象・動的秩序創発、相転移
- シンクロナイゼーション・カオス・非線形効果・引き込み
- 適応進化・ゲーム理論・スモールワールド・セルラーオートマトン

研究テーマ

- 脳における情報処理機構の解明
- 生物システムの動的秩序創発のメカニズム
細胞集団(免疫系の自己・非自己)、魚群の行動、
人間社会の付き合い行動 など

脳の情報処理機構

- **ボトムアップ的アプローチ**
たんぱく質や遺伝子、細胞などの構成要素について**現実的でミクロスコピックなモデル**を作り、それを用いて、簡単なシステムを構築し、そのシステムモデルを用いて**さらに上位のシステムを構築していく**という、下からの積み上げ方式である。

脳の情報処理機構

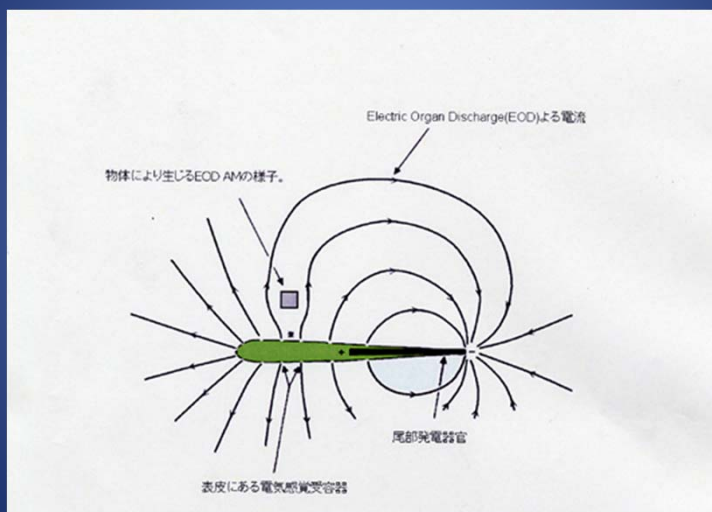
- **トップダウン的アプローチ**

構成要素のモデルはできる簡単にして、システム全体の状態や機能についてどのようなものが生じてくるのかを調べる。システム全体の働きをある程度理解してから、サブシステムさらには構成要素をより現実的なものに近づけていく方式である。

ボトムアップ的アプローチ

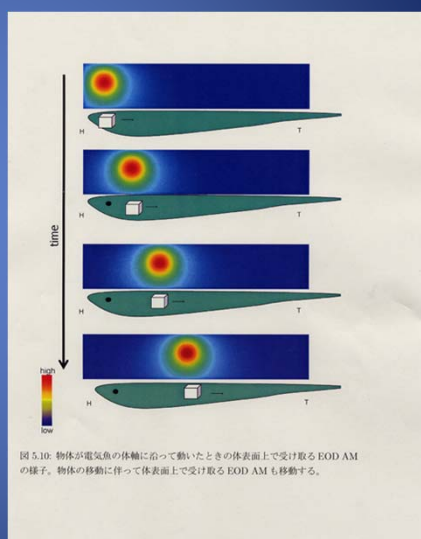
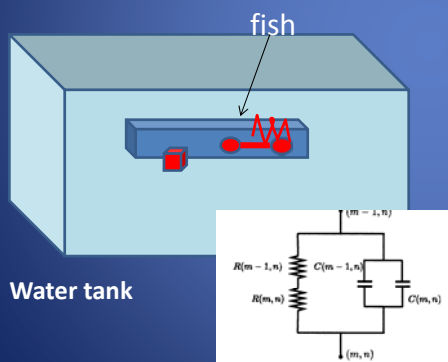


Electrolocation



Electric image

Calculation of electric image by finite-element method



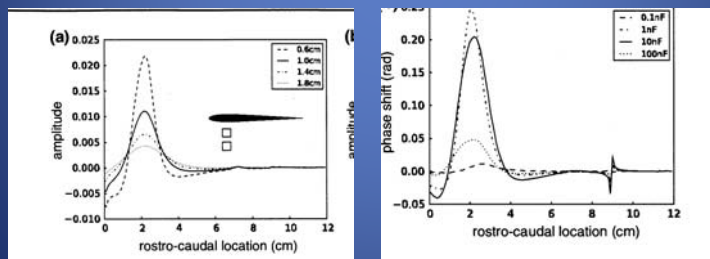
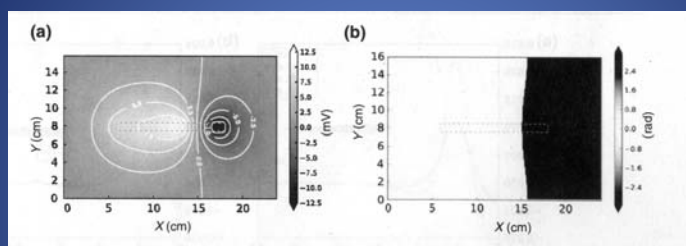
Equations of EOD calculation

$$I(m-1, n; m, n) = Y(m-1, n; m, n)(V(m-1, n) - V(m, n)),$$

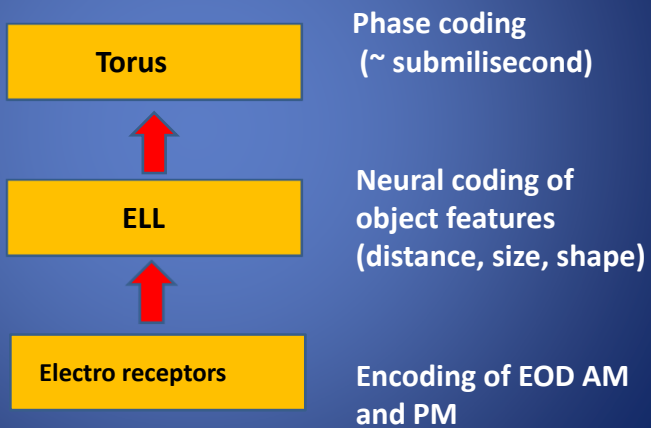
$$Y(m-1, n; m, n) = \frac{1}{R(m-1, n) + R(m, n)} + i\omega(C(m-1, n) + C(m, n)),$$

$$V(m, n) = \frac{\sum_{X=m-1, m+1} Y(X, n; m, n)V(X, n) + \sum_{X=n-1, n+1} Y(m, X; m, n)V(m, X)}{\sum_{X=m-1, m+1} Y(X, n; m, n) + \sum_{X=n-1, n+1} Y(m, X; m, n)},$$

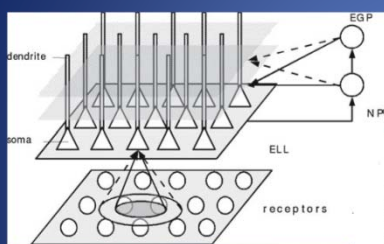
Electric image



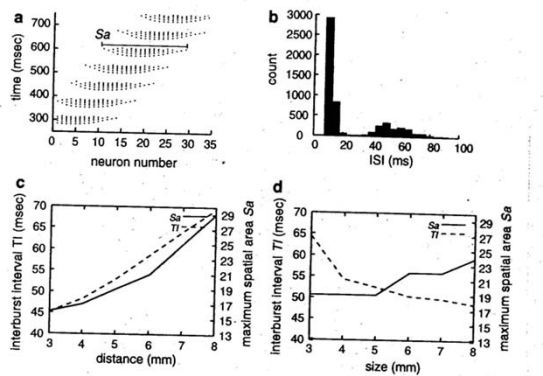
Neural pathway



Burst coding of object features



Distance and size



Neuron model

Soma

$$\frac{dV_{ij}^S}{dt} = I_{Na,S} + I_{Dr,S} + I_{leak}^S + \frac{g_c}{K} (V_{ij}^D - V_{ij}^S) + I_{FF,E}^{ij} + I_{FB,I}^{ij}$$

Dendrite

$$\frac{dV_{ij}^D}{dt} = I_{Na,D} + I_{Dr,D} + I_{leak}^D + \frac{g_c}{1-K} (V_{ij}^S - V_{ij}^D) + I_{FB,E}^{ij} + I_{FB,I}^{ij}$$

Where

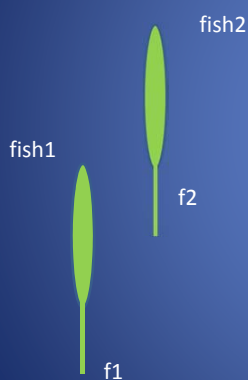
$$I_{Na,S} = g_{Na,S} \cdot m_{\infty,S}^2 (V_{ij}^S) \cdot (1 - n_S) (V_{Na} - V_{ij}^S), \quad I_{Dr,S} = g_{Dr,S} \cdot n_S^2 \cdot (V_K - V_{ij}^S),$$

$$I_{leak}^S = g_{leak} (V_{ij} - V_{ij}^S),$$

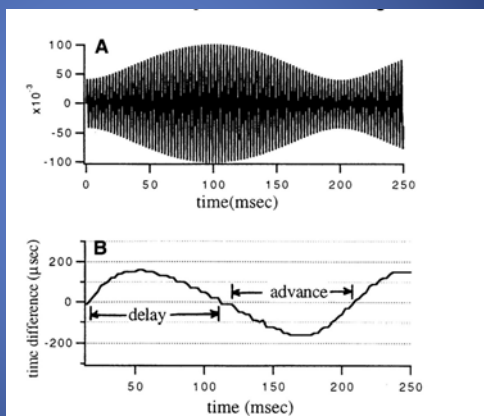
$$I_{Na,D} = g_{Na,D} \cdot m_{\infty,D}^2 (V_{ij}^D) \cdot h_D (V_{Na} - V_{ij}^D), \quad I_{Dr,D} = g_{Dr,D} \cdot n_D^2 \cdot p_D (V_K - V_{ij}^D),$$

$$I_{leak}^D = g_{leak} (V_{ij} - V_{ij}^D), \quad \frac{dn_S}{dt} = \frac{n_{\infty,S}(V_{ij}^S) - n_S}{\tau_{n,S}}, \quad \frac{dX_D}{dt} = \frac{X_{\infty,D}(V_{ij}^D) - X_D}{\tau_{X,D}} \quad (X = h, n, p).$$

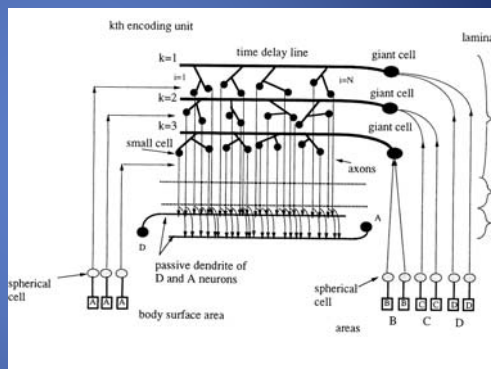
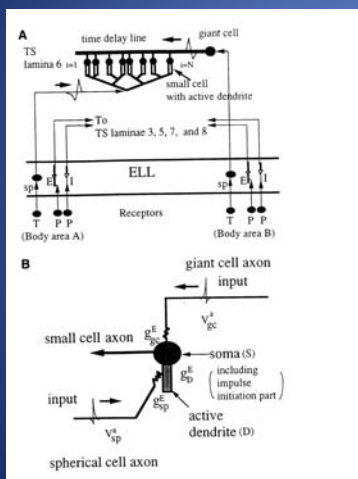
Detection of phase difference



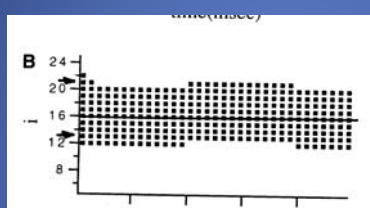
$$Df = f1 - f2$$



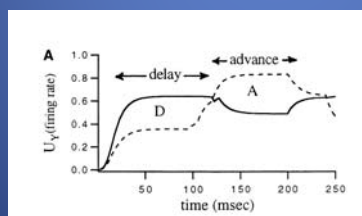
Model

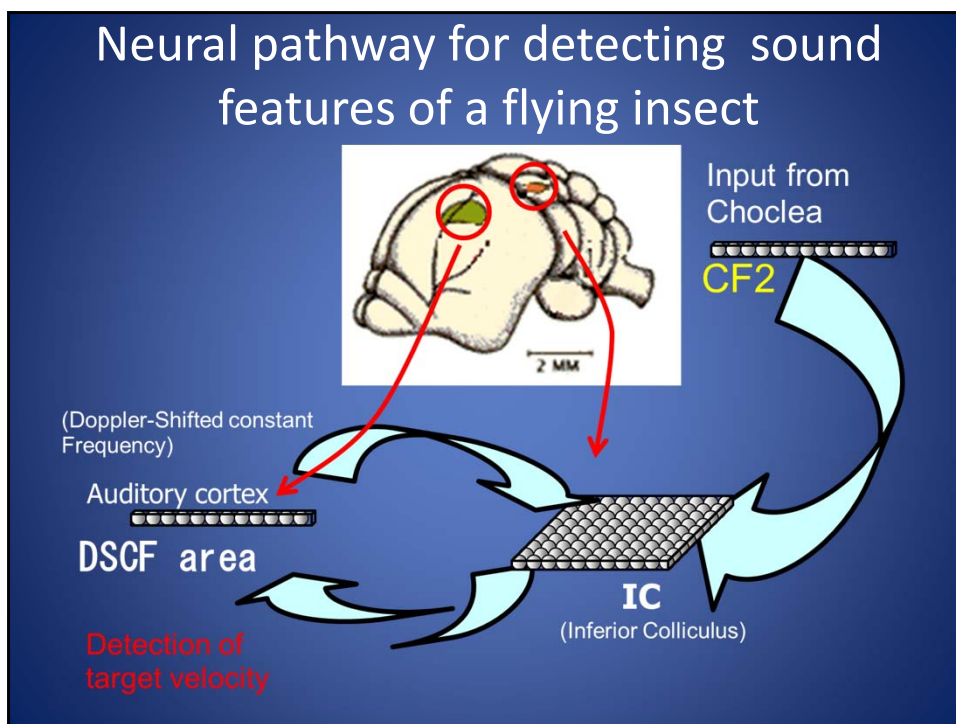
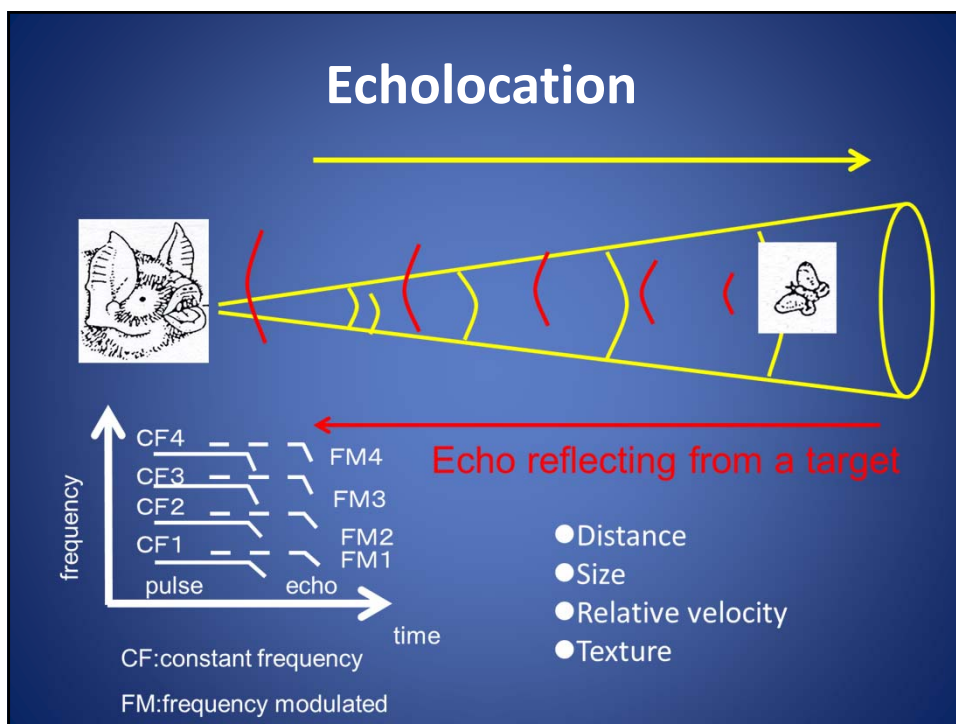


Detection of time difference of submilliseconds

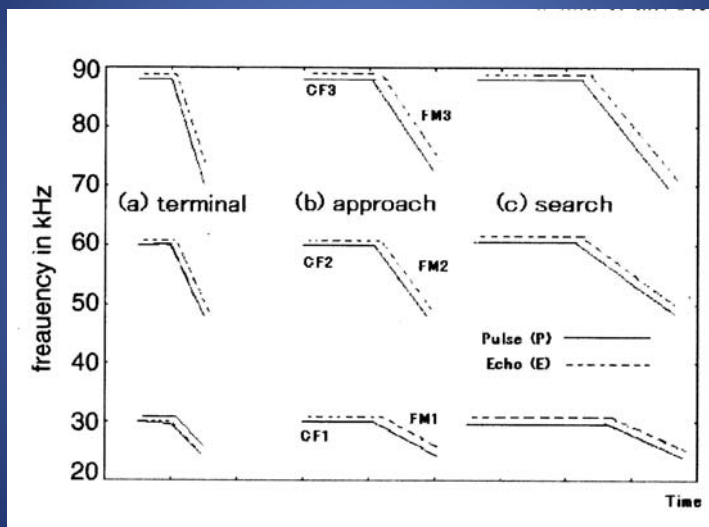


TD=2 microsec





FM slope



Network model

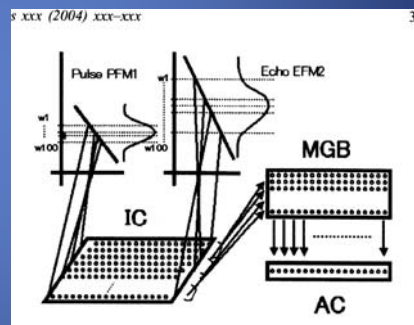
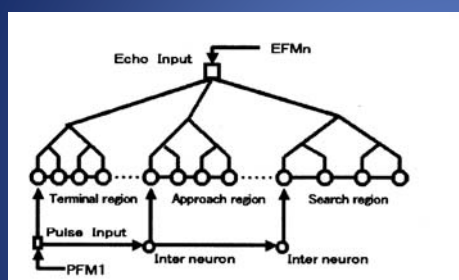
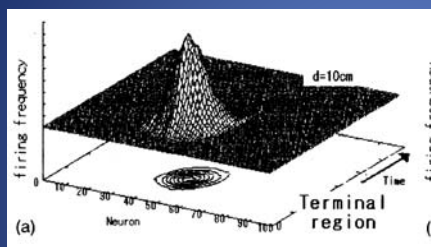


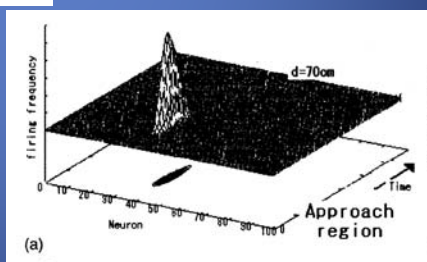
Fig. 3. Neural model of multiple time-disparity detection (TDD).

Responses of IC neurons

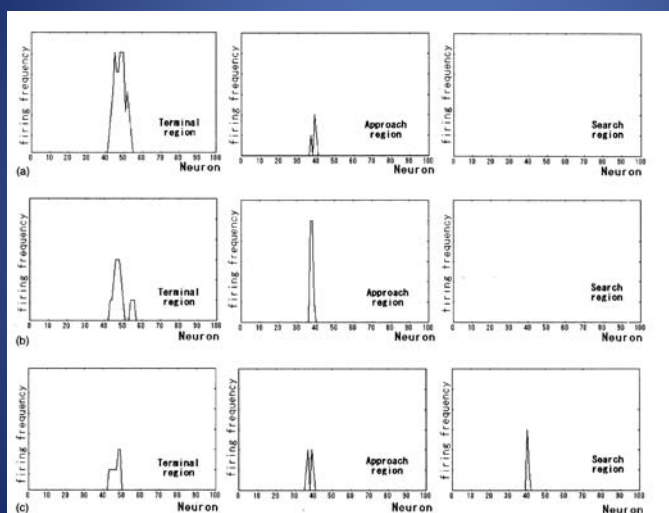


$R_s=6/2\text{kHz}$

$R_s=6/3\text{kHz}$



Responses of AC neurons



(step)

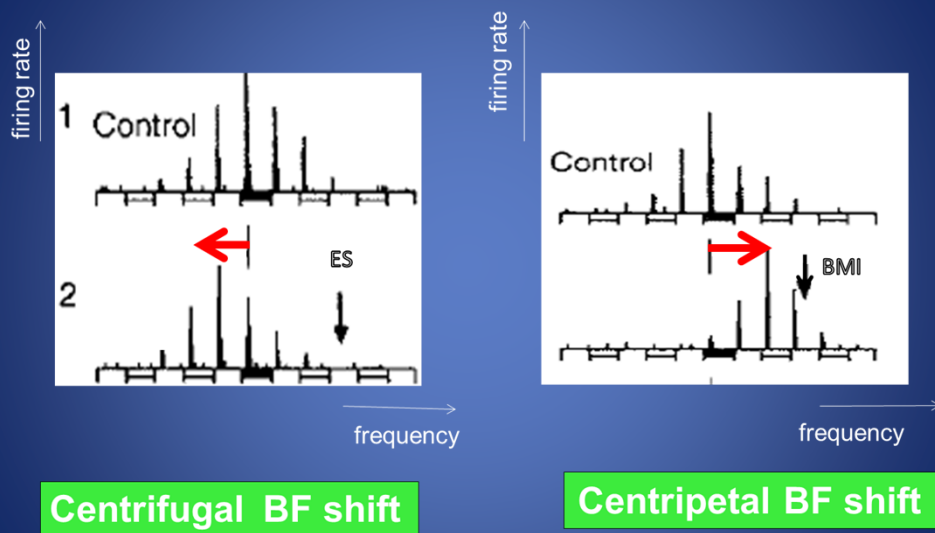
6/4 kHz/ms

6/3 kHz/ms

6/2 kHz/ms

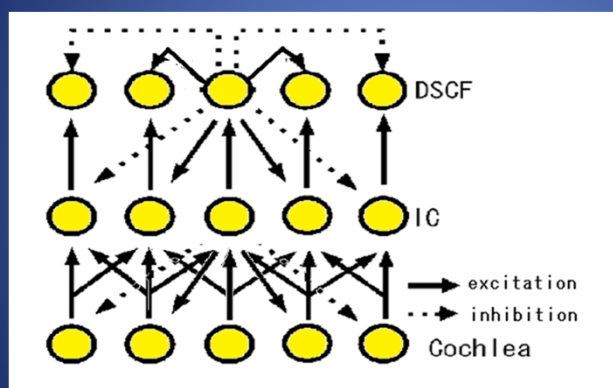
(gentle)

Two types of BF shifts in IC

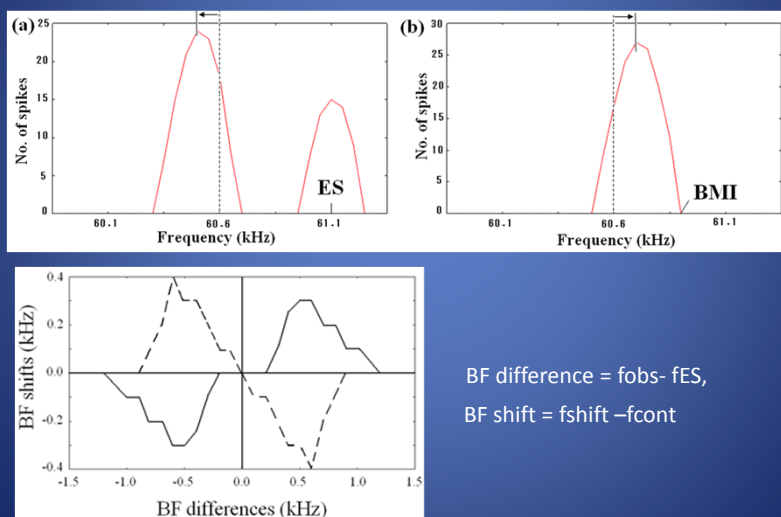


(Xiao and Suga, 2002)

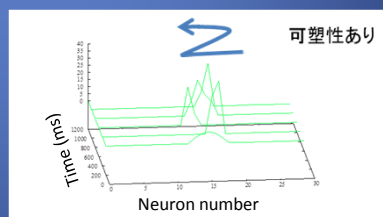
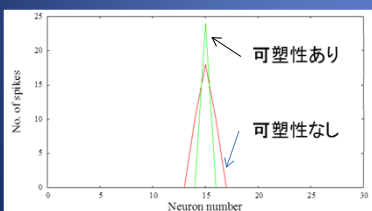
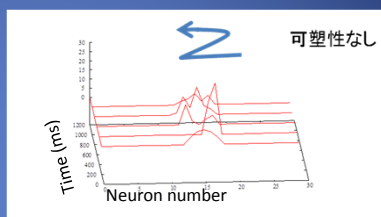
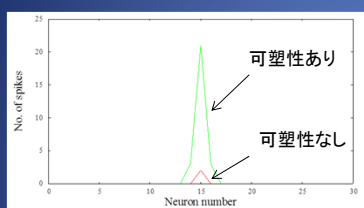
Network model



Results



Roles of synaptic plasticity



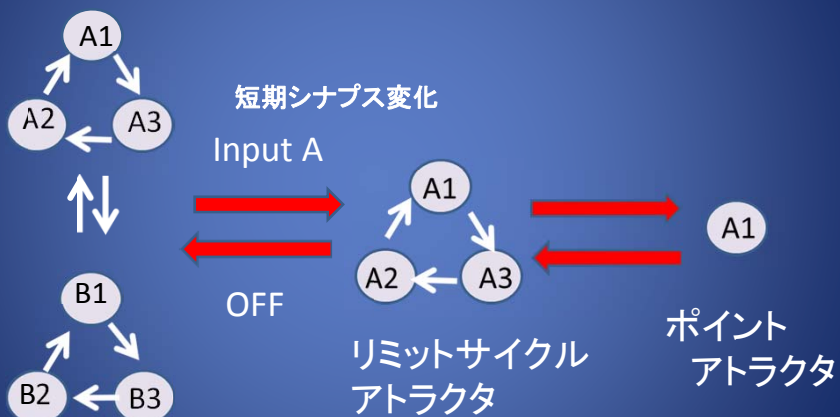
Future works

- Electrolocation: electric image, neural coding of target distance and its size, hyperacuity of phase information,
→ shape ?
- Echolocation: neural coding of target distance, neural mechanism of corticofugal modulation of tuning property
→ detection of a flying insect ?
- Sound localization: information processing of IID and ITD, binding mechanism
→ head direction, attention ?

トップダウン的アプローチ

- 動的アトラクタ
- 嗅覚
- 視覚
- 聴覚

Dynamical attractor model 記憶の階層的表現



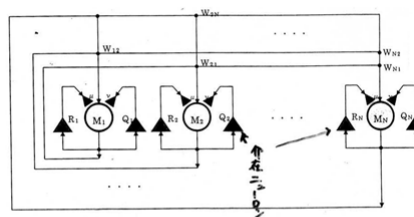
Network model

$$\tau_{mj} \frac{du_{mj}(t)}{dt} = -u_{mj}(t) + \sum_{j=1}^N \sum_{d_{ij}=0}^{d_{\max}} w_{mm,ij}(t, d_{ij}) \cdot V_{mj}(t - d_{ij})$$

$$+ w_{mq} U_{qi}(t) + w_{mr} U_{ri}(t) + I_i(t),$$

$$\tau_{qi} \frac{du_{qi}(t)}{dt} = -u_{qi}(t) + w_{qm} V_{mi}(t),$$

$$\tau_{ri} \frac{du_{ri}(t)}{dt} = -u_{ri}(t) + w_{rm} V_{mi}(t).$$

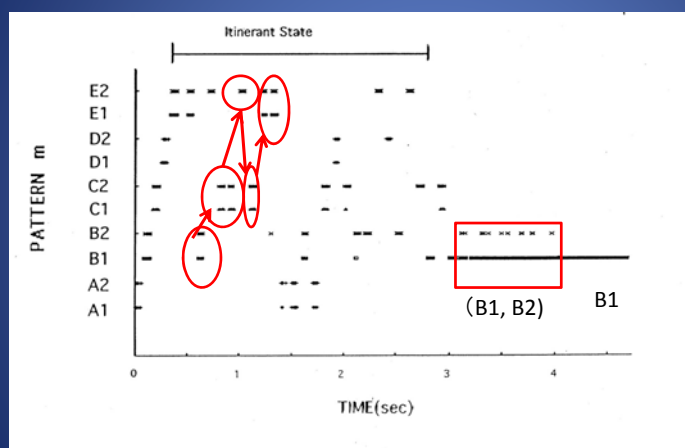


学習則

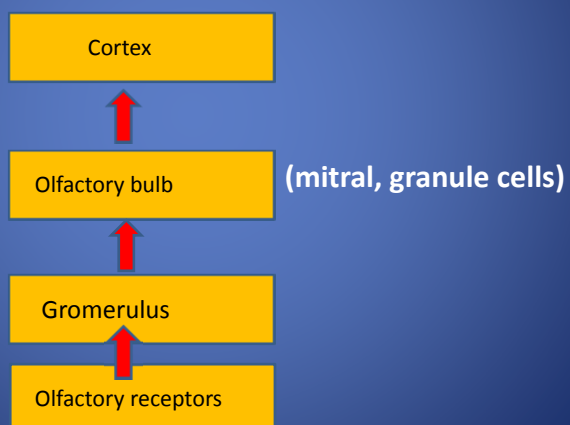
$$\tau_{wmm} \frac{dw_{mm,ij}(t, d_{ij})}{dt} = -w_{mm,ij}(t, d_{ij})$$

$$+ \varepsilon V_{mi}(t) \cdot V_{mj}(t - d_{ij}).$$

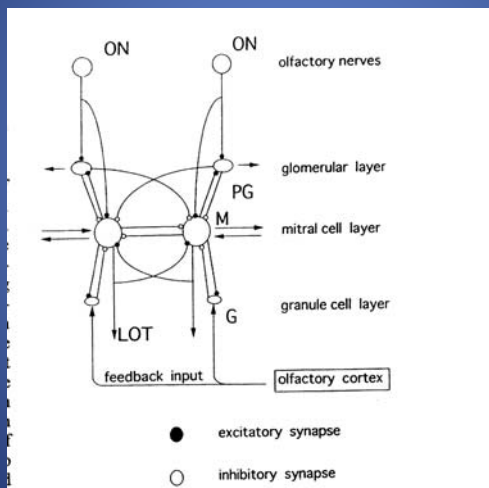
Chaotic itinerant state



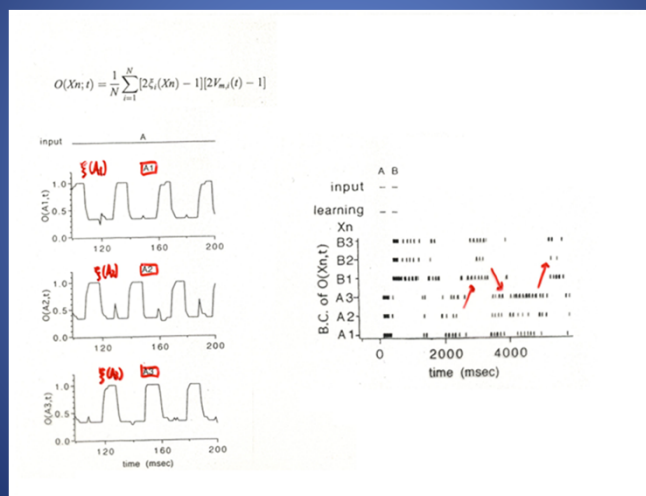
Neural pathway of olfactory processing



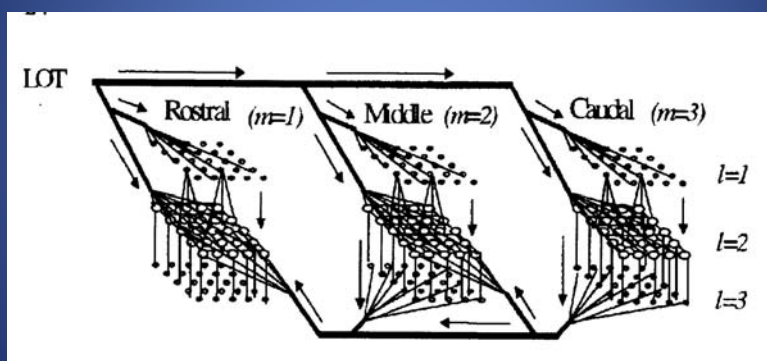
Model



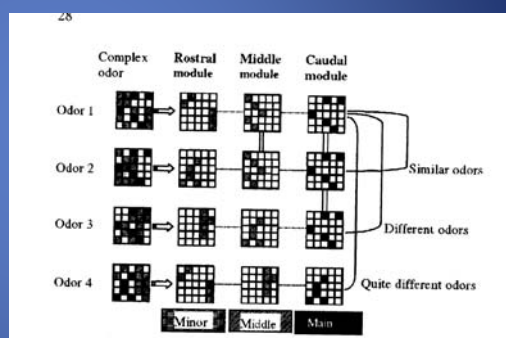
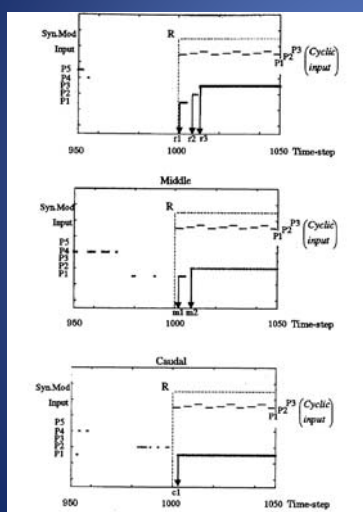
Coding of odor information in olfactory bulb



Neural network model of olfactory cortex



Hierarchical discrimination of odor components



Neural mechanism of visual categorization

Four features of drawing faces

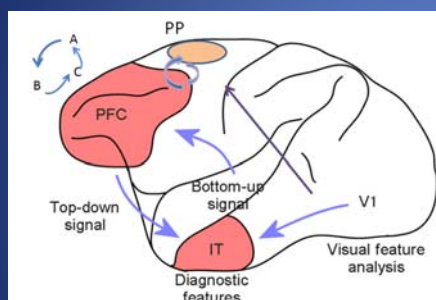
Eye separation
Eye height
Nose length
Mouth height



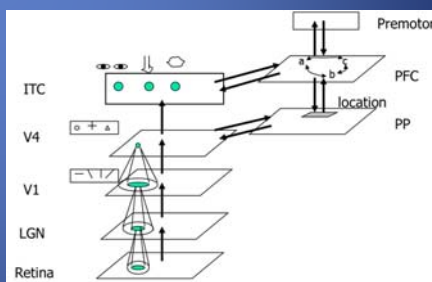
After the learning of categorization task, IT neurons sensitive to eye separation and eye height exhibit increased firing rates, while those sensitive to the other features remain unchanged the firing rates.

(Sigala & Logothetis, 2000)

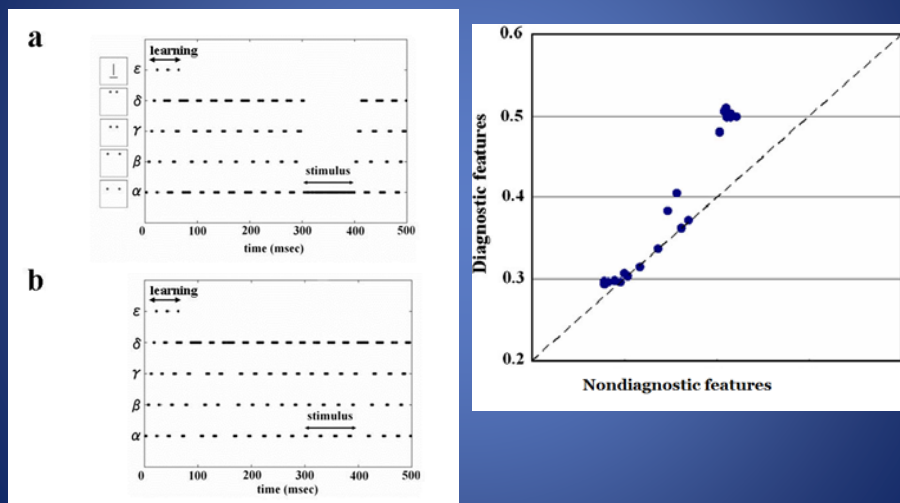
Neural mechanism for visual categorization



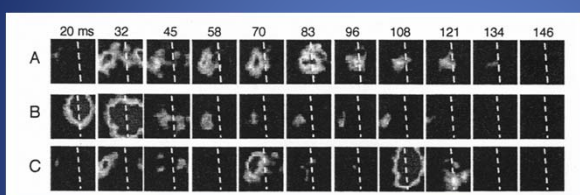
Model



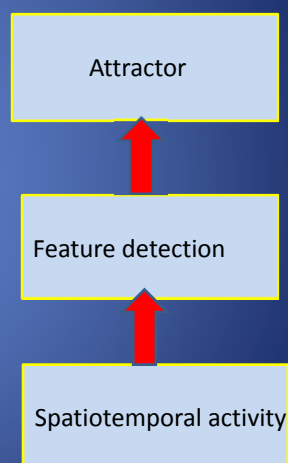
Responses of IT and PFC neurons

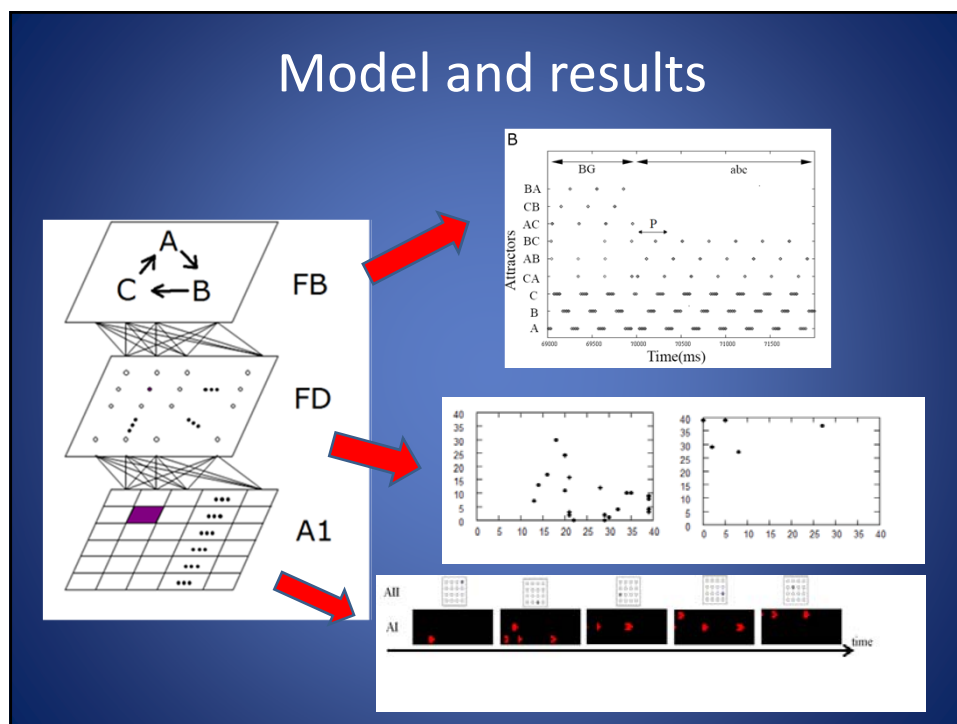


Hierarchical processing of auditory information



(Horikawa et al. 1996)





Attractor models

- Olfactory system
- Visual system
 - categorization, face perception, attention
- Auditory system
 - word perception, information processing in A1
- Gustatory system
- Somatosensory system (tactile, haptic)