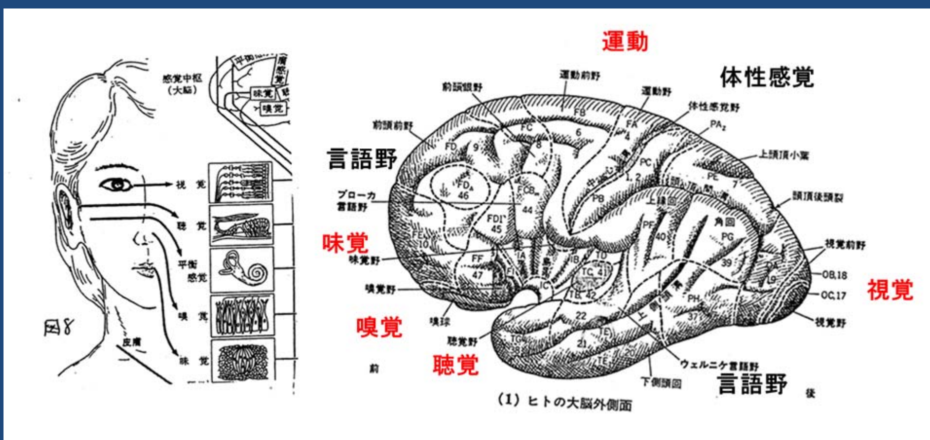
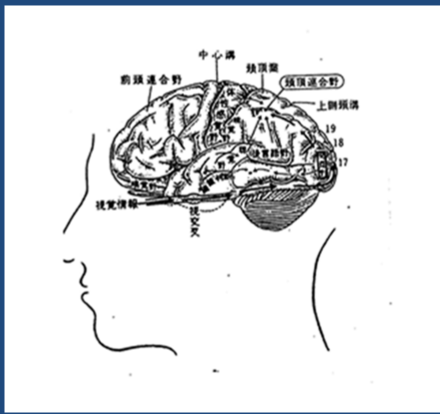
感覚情報の階層的処理機構

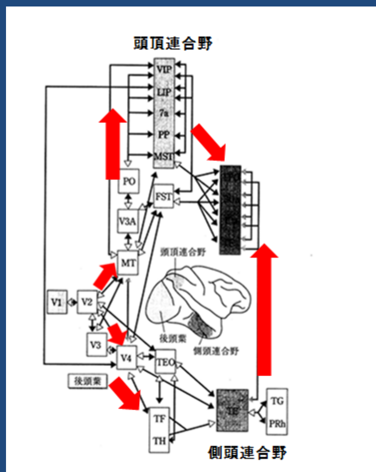
先進理工学専攻
樫森　与志喜

感覚受容と脳内の機能的地図



視覚経路

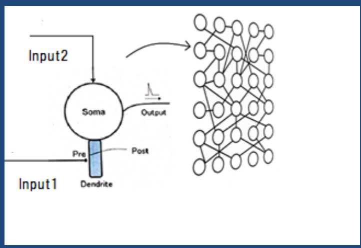




視覚経路とその情報処理

大脳皮質の神経細胞

大脳皮質は6層構造を取り、ざまざまな形態の神経細胞で構成されている。



Models of a single neuron
Network models

➡ Highly nonlinear system

Hodgkin-Huxley model

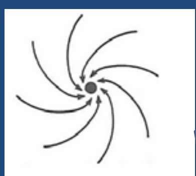
$$dV_M/dt = (1/C_M)[I - \{\bar{g}_K n^4 (V_M - V_K) + \bar{g}_{Na} m^3 h (V_M - V_{Na}) + \bar{g}_{Cl}(V_M - V_{Cl})\}]$$

$$dn/dt = \alpha_n - (\alpha_n + \beta_n)n \qquad dh/dt = \alpha_h - (\alpha_h + \beta_h)h$$

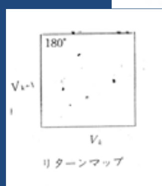
$$dm/dt = \alpha_m - (\alpha_m + \beta_m)m$$

力学系の解の振る舞い

Point attractor

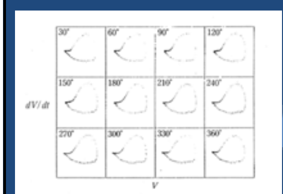


Limit cycle

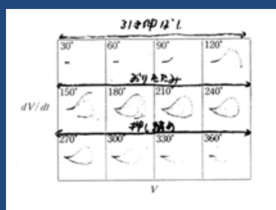


Hodgkin-Huxley Equation

$$\frac{d\vec{x}}{dt} = f(\vec{x}, t)$$

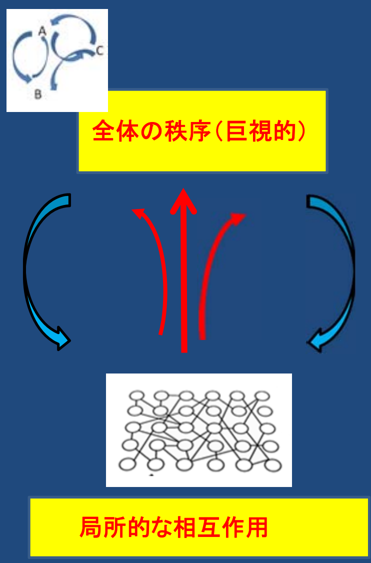


Quasi-periodic



Chaotic attractor

注目すべきこと



●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

研究に関連するキーワード

- 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・アトラクタ・カオス・非線形効果・引き込み

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

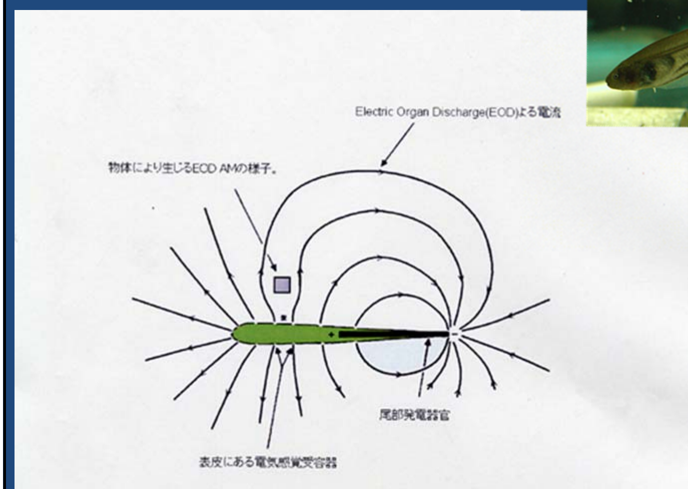
脳の情報処理機構

- ボトムアップ的アプローチ

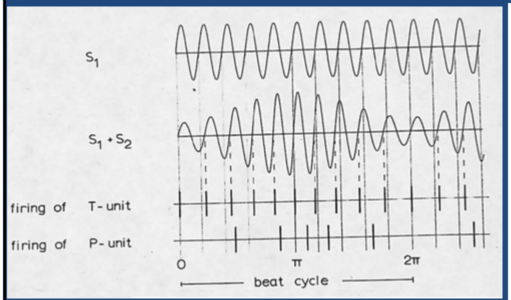
たんぱく質や遺伝子、細胞などの構成要素について現実的でミクロスコピックなモデルを作り、それを用いて、簡単なシステムを構築し、そのシステムモデルを用いてさらに上位のシステムを構築していくという、下からの積み上げ方式である。

ボトムアップ的アプローチ

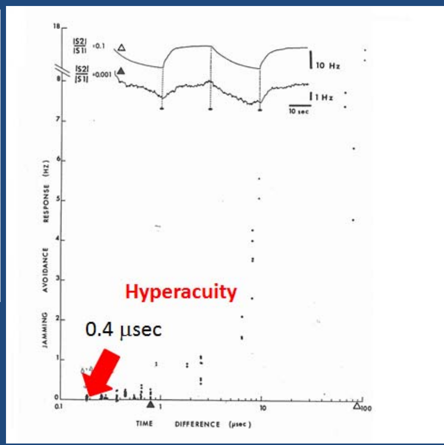
Electrolocation



Amplitude and phase coding

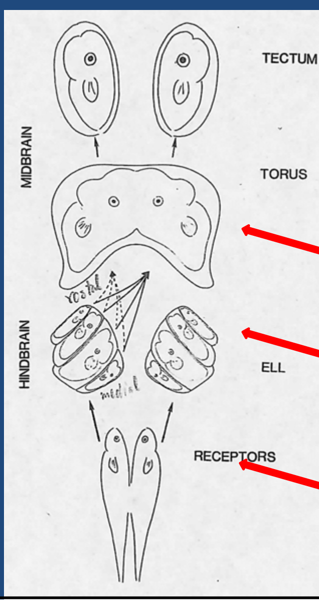


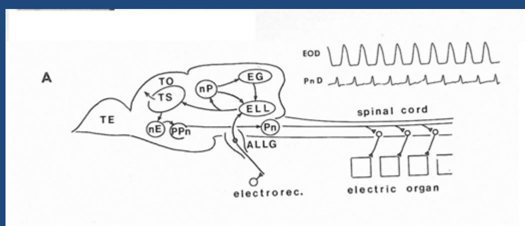
Detection ability of phase difference



(Hyperacuity; Y. Kashimori et al., Biol Cybern, 2001)

The neural pathway of electrosensory processing





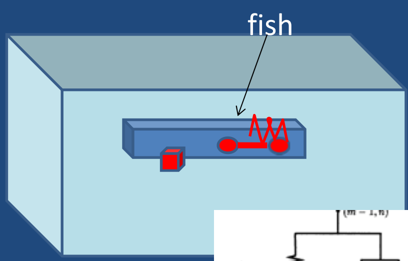
Phase coding
(~ submilisecond)

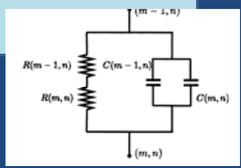
Neural coding of object features (distance, size, shape)

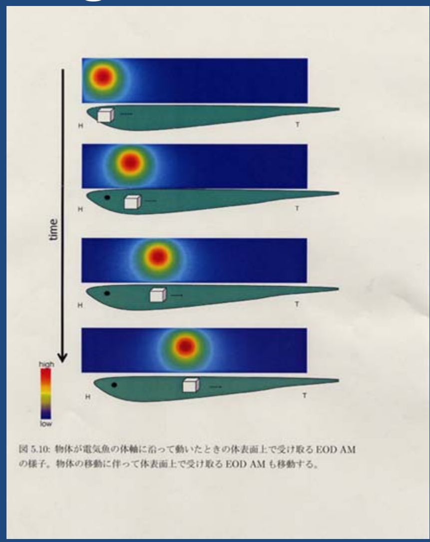
Encoding of EOD AM and PM

Electric image

Calculation of electric image by finite-element method

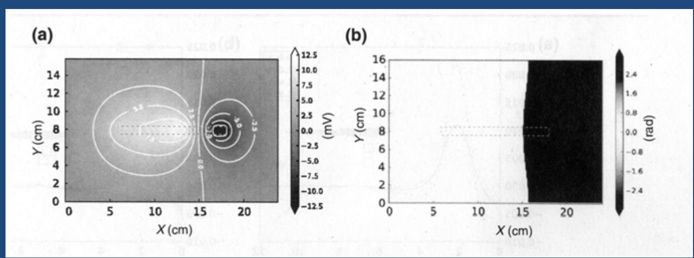


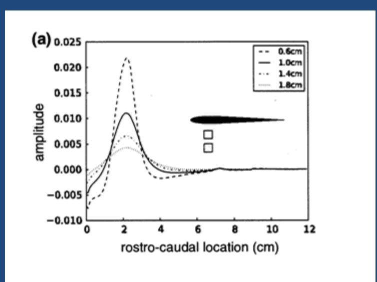


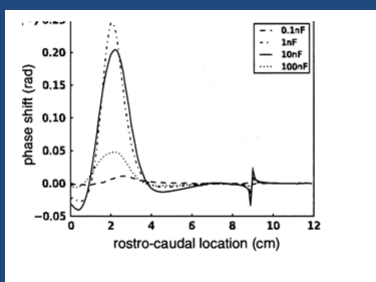


(Fujita and Kashimori, Biol Cybern ,2010)

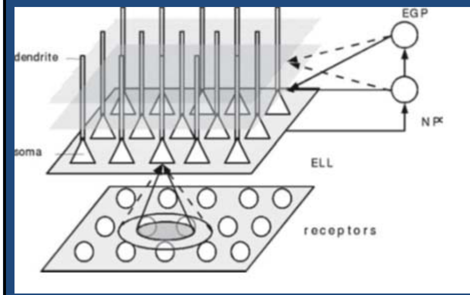
Electric image







Burst coding of object features



Object

Neuron model

Soma

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

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

Dendrite

Where

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

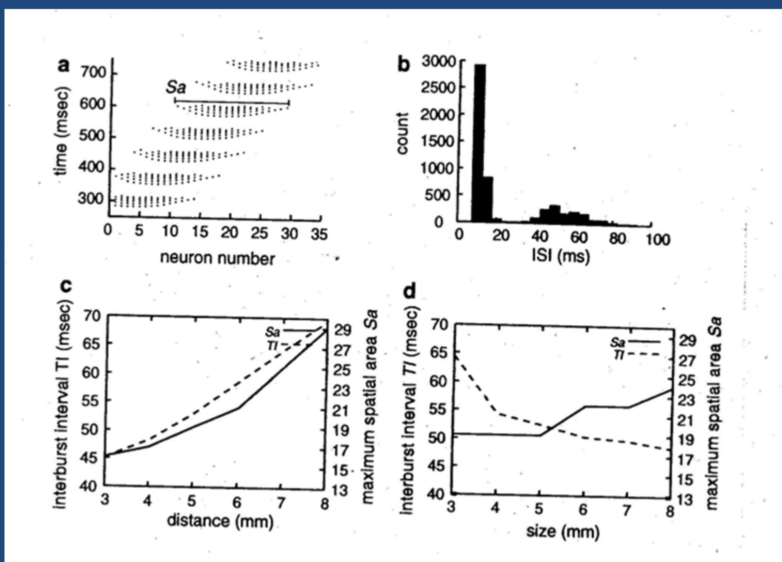
$$I_{leak}^S = g_{leak}(V_l - V_{ij}^S),$$

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

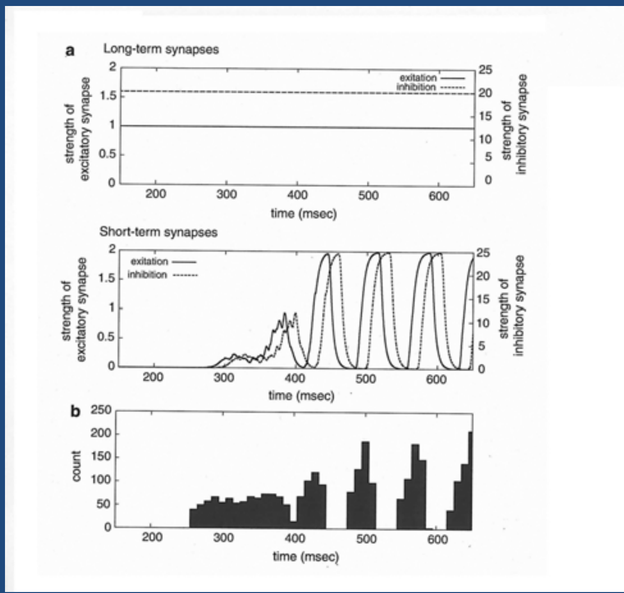
$$I_{leak}^D = g_{leak}(V_l - V_{ij}^D), \qquad \frac{dn_S}{dt} = \frac{n_{\infty,S}(V_{ij}^S) - n_S}{\tau_{n,S}}, \qquad \frac{dX_D}{dt} = \frac{X_{\infty,D}(V_{ij}^D) - X_D}{\tau_{X,D}} \quad (X = h, n, p).$$

(Fujita et al., Biol Cybern, 2007)

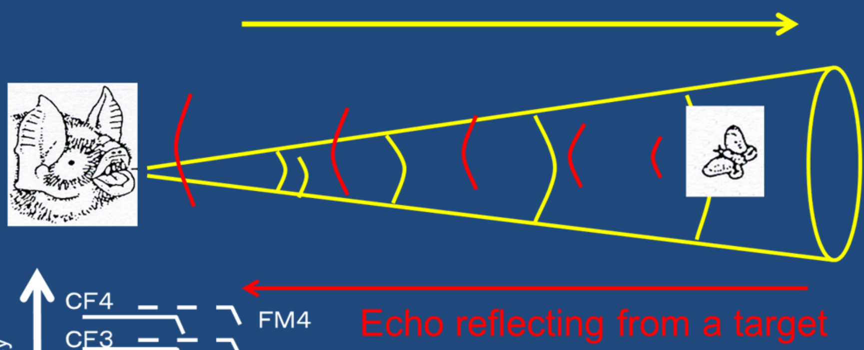
Distance and size

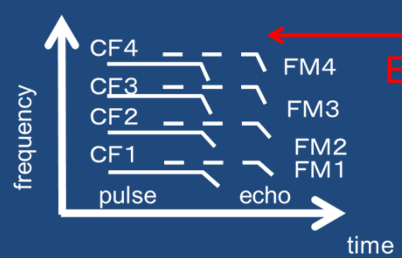


The role of feedback in burst coding



Echolocation



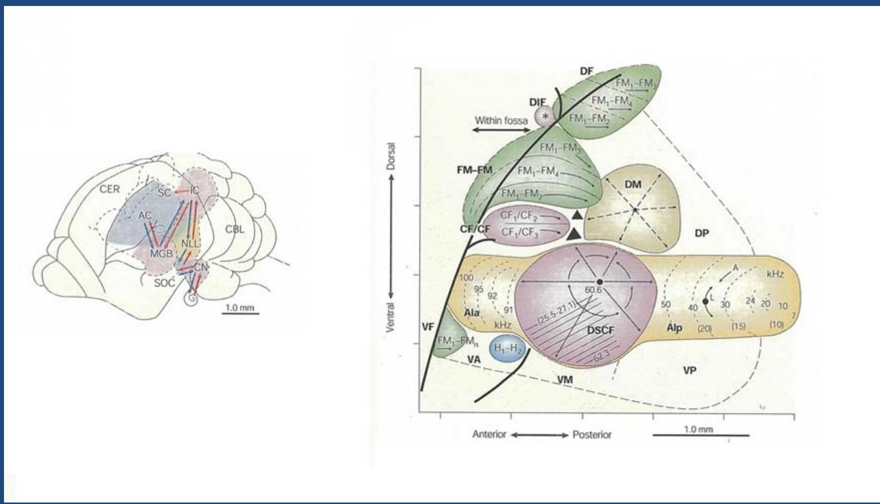


CF:constant frequency

FM:frequency modulated

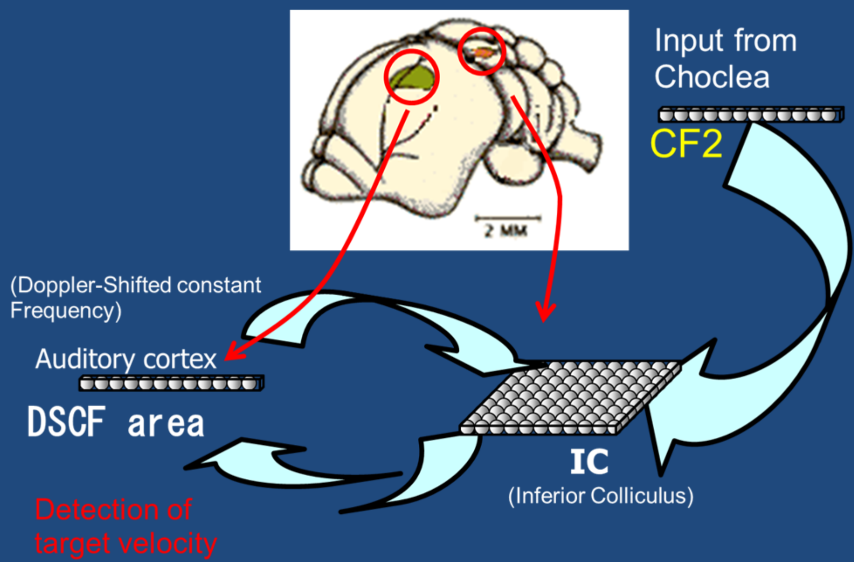
- Distance
- Size
- Relative velocity
- Texture

The brain and the auditory cortex of the mustached bat



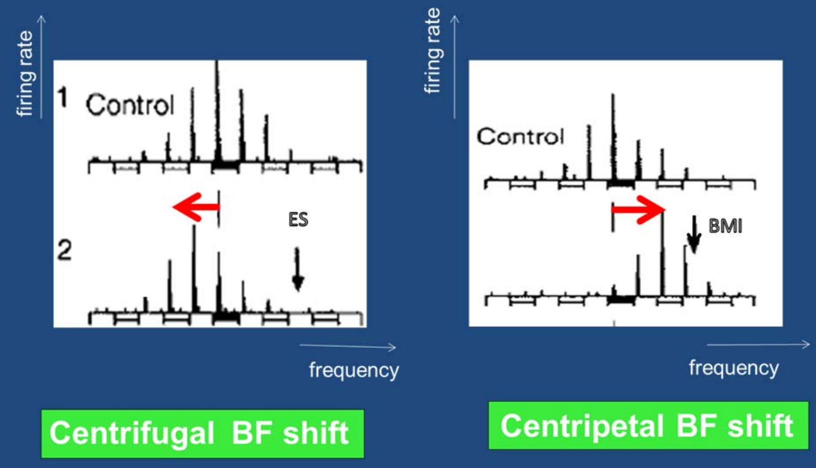
(Suga and Xiao 2001)

Neural pathway for detecting sound features of a flying insect



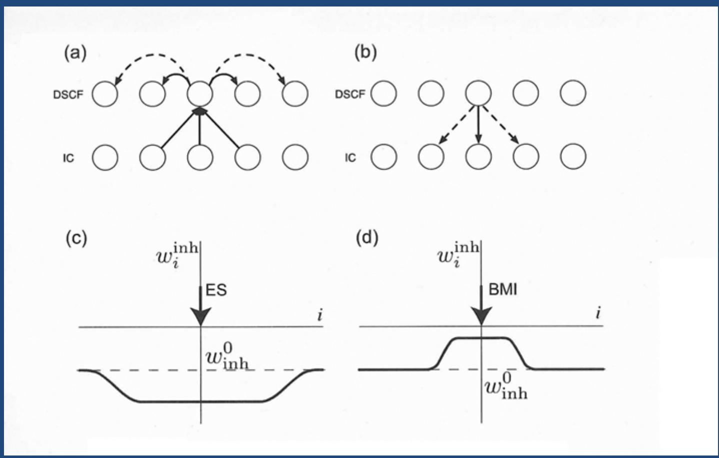
Egocentric selection

Two types of BF shifts in IC



(Xiao and Suga, 2002)

Network model



(Fujita and Kashimori, Neural Proc Lett, 2015)

Equations of the network model

$$\frac{dV_i^{\mathrm{IC}}}{dt} = 0.04(V_i^{\mathrm{IC}})^2 + 5V_i^{\mathrm{IC}} + 140 - u_i^{\mathrm{IC}} + \sum_{j=1}^{N} X_{ij}^{\mathrm{IC-DC}} + \xi_i^{\mathrm{IC}}, \quad (1)$$

$$\frac{du_i^{\mathrm{IC}}}{dt} = \lambda a(bV_i^{\mathrm{IC}} - u_i^{\mathrm{IC}}), \quad (2)$$

where

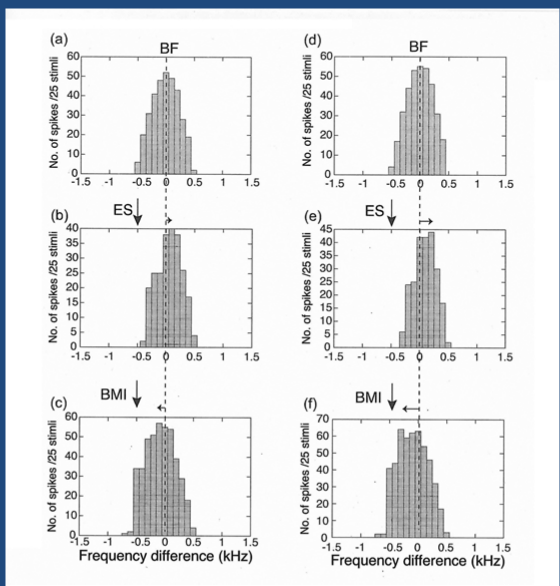
$$I_i^{\mathrm{IC}} = I_0^{\mathrm{IC}} \exp\left(-\frac{(i-i_0)^2}{\sigma_{\mathrm{Ch}}^2}\right). \quad (3)$$

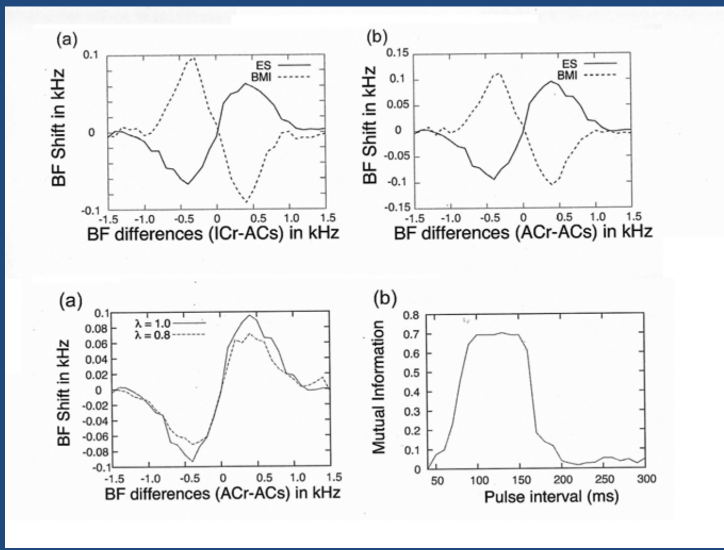
$$\tau_{\mathrm{PSP}} \frac{dX_{ij}^{\mathrm{IC-DS}}}{dt} = -X_{ij}^{\mathrm{IC-DS}}, \quad (4)$$

$$w_{ij}^{\mathrm{IC-DS}} = w_{\mathrm{exc}}^{\mathrm{FB}} H(x_{\mathrm{exc}}^{\mathrm{IC}} - |i-j|) - w_{\mathrm{inh}}^{\mathrm{FB}} H(x_{\mathrm{inh}}^{\mathrm{IC}} - |i-j|). \quad (5)$$

$$H(x) = \begin{cases} 1 & x \geq 0, \\ 0 & x < 0, \end{cases}$$

Centrifugal and centripetal BF shifts





Future works

- Electrolocatin: 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 ?

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。

トップダウン的アプローチ

Dynamic processing of sensory information (Attractor models)

- Olfactory system

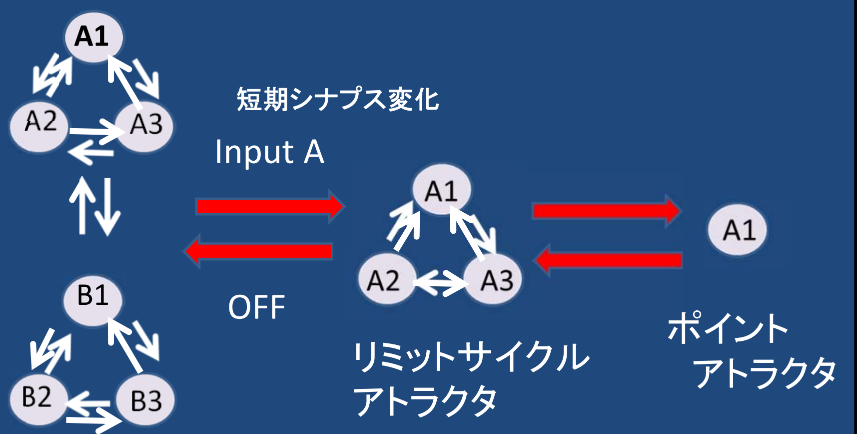
  odor information processing in olfactory bulb and piriform cortex
- Visual system

  categorization, face perception, top-down influence
- Auditory system

  word perception, information processing in A1
- Gustatory system

  Interaction between taste and odor information
- Somatosensory system (tactile, haptic)

Dynamical attractor model
記憶の階層的表現



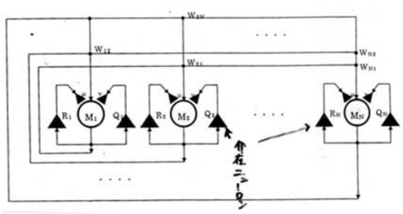
Network model

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

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

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

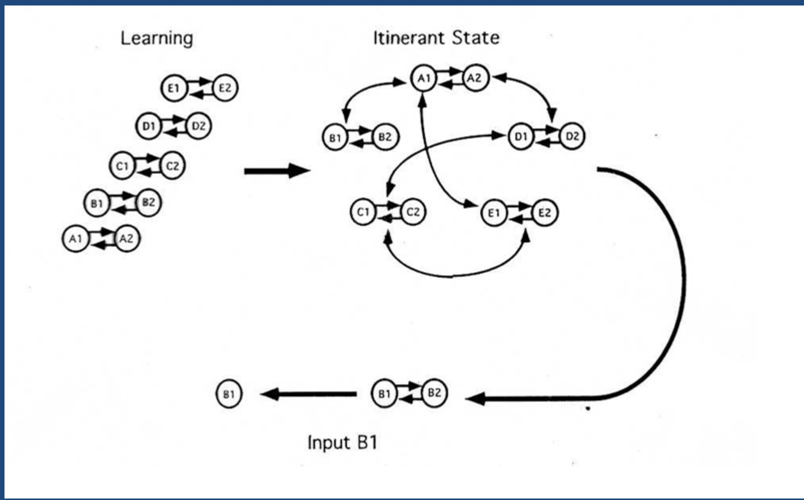
$$\tau_{ri}\frac{d\,u_{ri}(t)}{dt} = -u_{ri}(t) + w_{rm}V_{mi}(t).$$



学習則

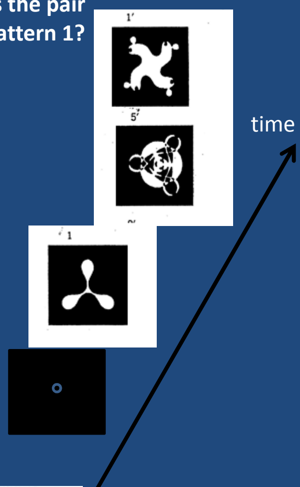
$$\tau_{wmm}\frac{d\,w_{mm,ij}(t,d_{ij})}{dt} = -w_{mm,ij}(t,d_{ij}) + \varepsilon V_{mi}(t)\cdot V_{mj}(t-d_{ij}).$$

Hierarchical processing in memory storage and recollection



Working memory in pair association task

Which is the pair of the pattern 1?



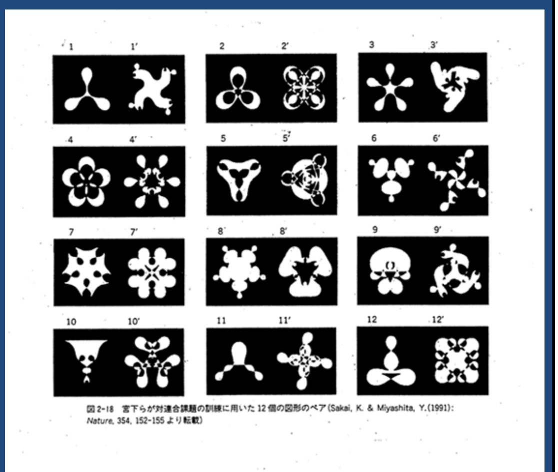
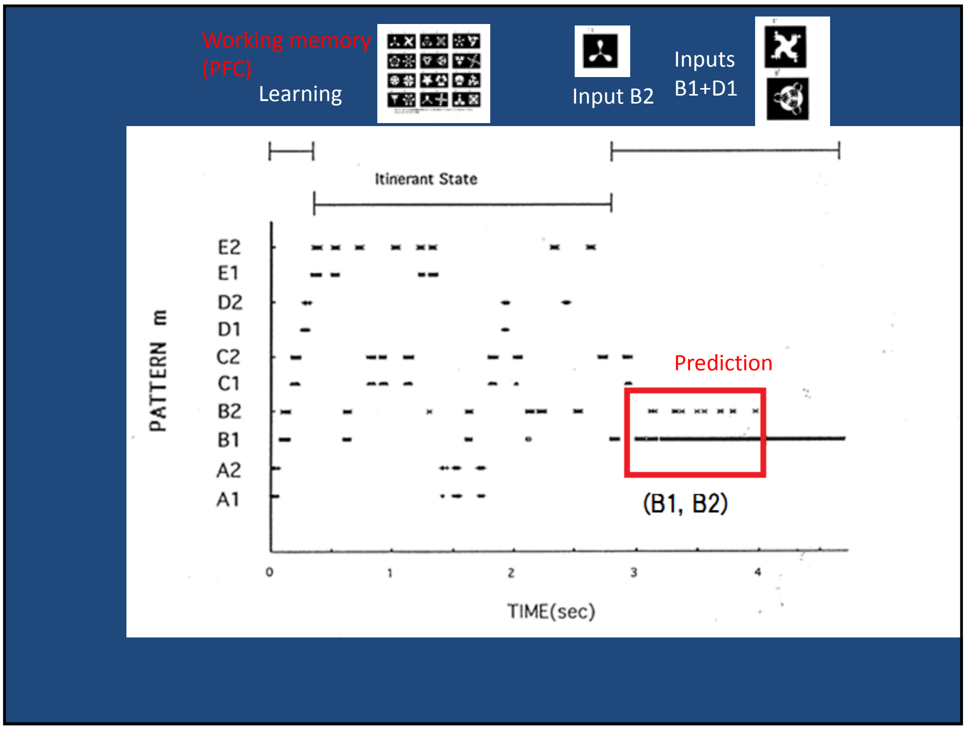


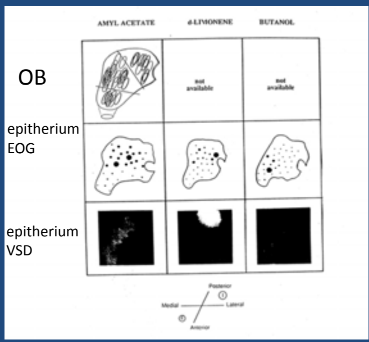
図 2-18　宮下らが対連合課題の訓練に用いた 12 個の図形のペア (Sakai, K. & Miyashita, Y. (1991): *Nature*, 354, 152-155 より転載)

(Sakai and Miyashita, 1991)

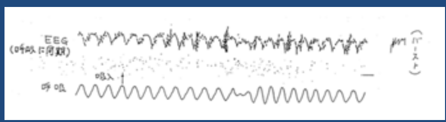


Dynamic coding of odor information

Dynamic coding of odor information



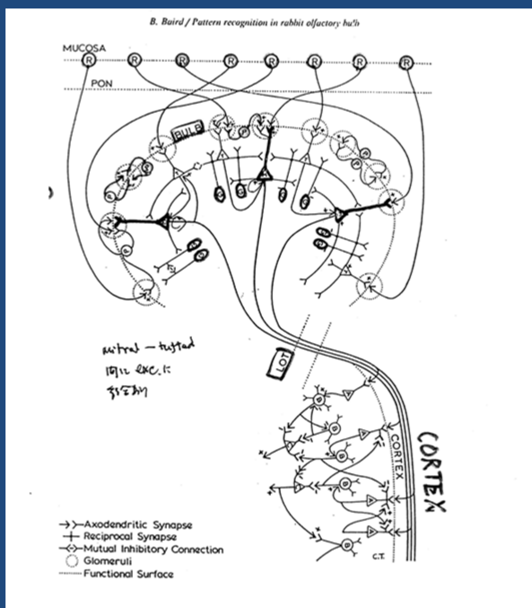
EEG



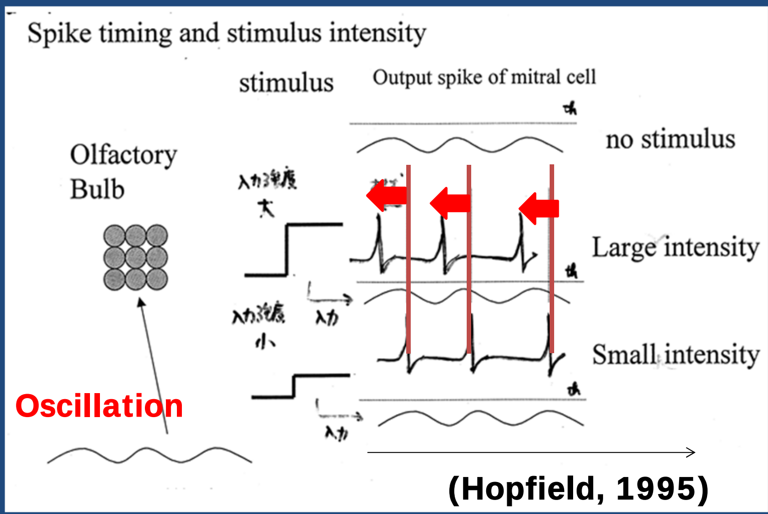
Neural model of olfactory system
W. Freeman (1987)

Spike coding of stimulus intensity
J.J. Hopfield (1995)

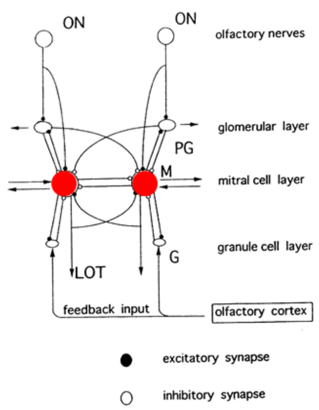
Neural pathway of olfactory processing



Spike coding of stimulus intensity



Neural network model of olfactory bulb



Equations

Mitral cell

$$\tau_{mj}\frac{du_{mj}(t)}{dt} = -u_{mj}(t) + \sum_{j=1}^{N}\sum_{d_{ij}=0}^{d_{max}} w_{mmij}(t,d_{ij})V_{mj}(t-d_{ij}) + \sum_{k=1(k\neq i)}^{N} w_{mpjk}V_{pk}(t) + w_{mq}U_{qj}(t) + I_{mj}(t)$$

Granule cell

$$\tau_{qj}\frac{du_{pj}(t)}{dt} = -u_{qj}(t) + w_{qm}U_{mj}(t) + I_{qm}$$

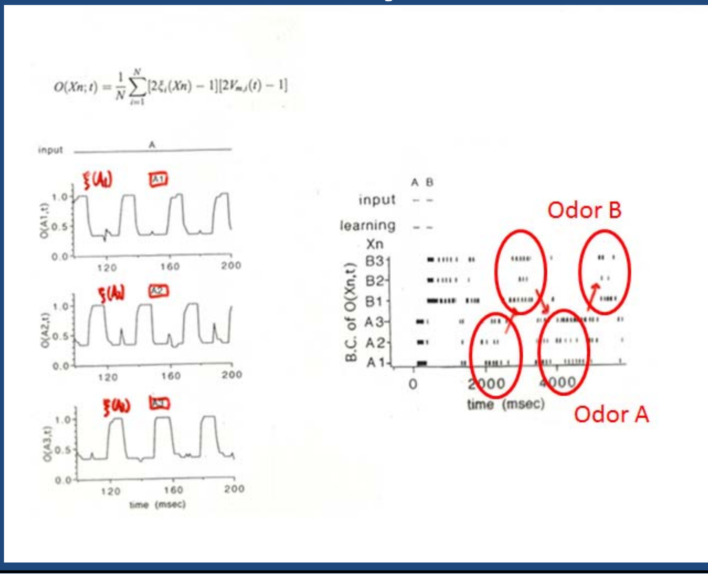
$$\Pr ob[V_{mj}(t)=1] = f_m[u_{mj}(t)]$$

$$\Pr ob[V_{qj}(t)=1] = f_p[u_{pj}(t)]$$

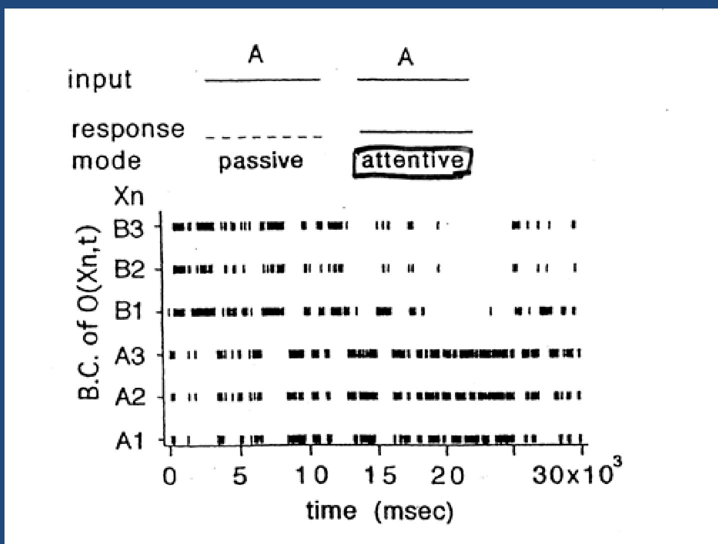
学習

$$\tau_{wmm}\frac{dw_{mmij}(t,d_{ij})}{dt} = -w_{mmij}(t,d_{ij}) + \eta V_{mi}(t)V_{mj}(t-d_{ij})$$

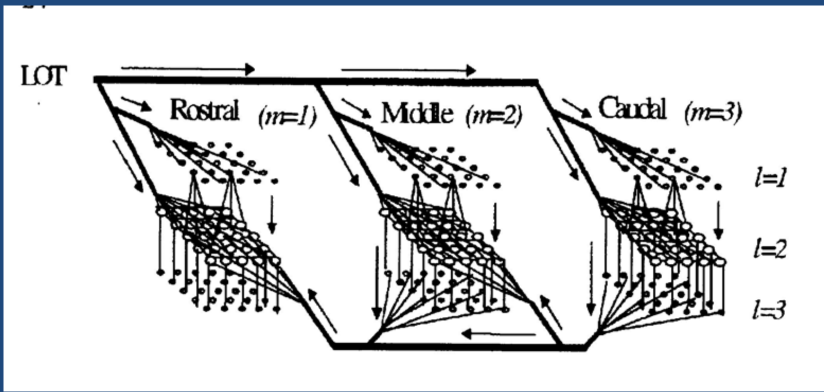
Coding of odor information in olfactory bulb



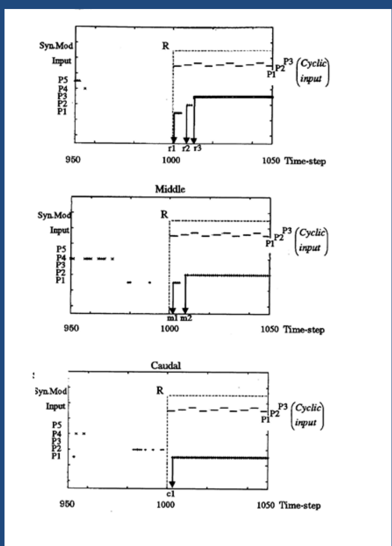
Representation of odor information by dynamical attractors

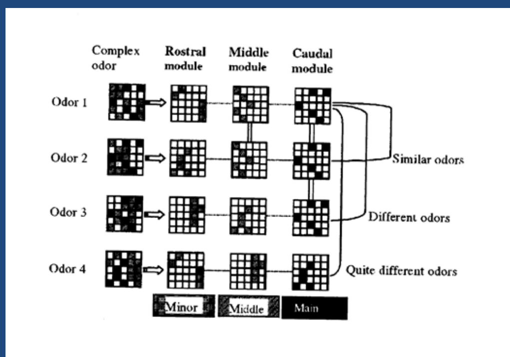


Neural network model of olfactory cortex



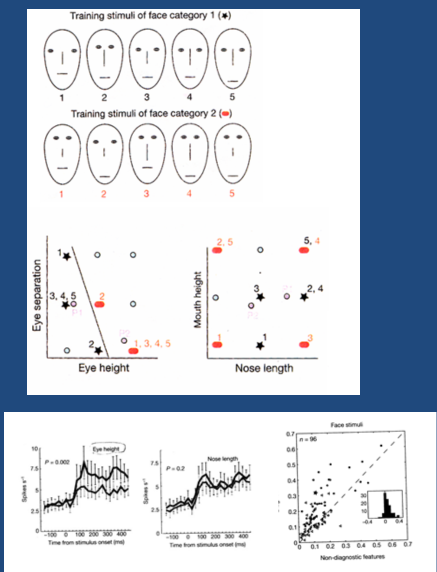
Hierarchical discrimination of odor components



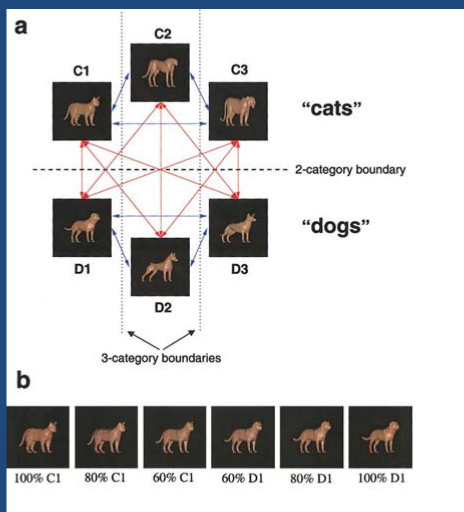


Neural mechanism of visual categorization

Visual categorization

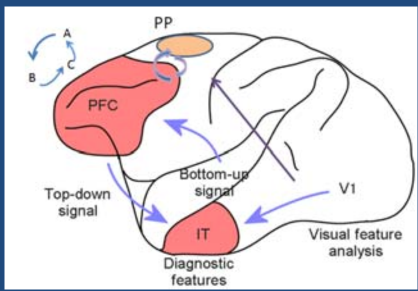


(Sigala & Logothetis, 2000)

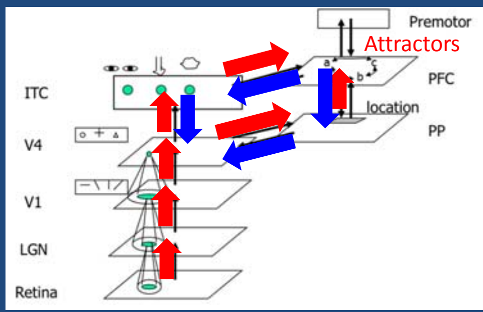


(Freedman et al., 2001)

Neural mechanism for visual categorization



Model



(Soga and Kashimori, Vision Res, 2008)

Equations of PP neurons

$$\tau_{PP}\frac{dV^{ij}_{PP}}{dt} = -V^{ij}_{PP} + \sum_{k,l,m} w^{FF}_{V4-PP}(ij;kl,m)X_{V4}(kl,m) + I^{FB}_{PFC-PP},$$

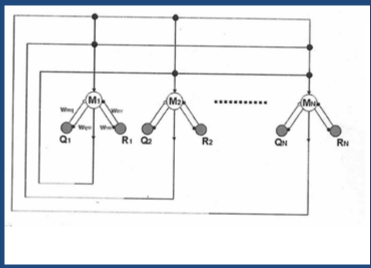
$$X^{ij}_{PP} = \frac{1}{1+\exp\left(-\left(V^{ij}_{PP} - V^{th}_{PP}\right)/\varepsilon_{PP}\right)},$$

Equations of ITC neurons

$$\tau_{ITC}\frac{dV^{l}_{ITC}}{dt} = -V^{l}_{ITC} + \sum_{ij,k} w_{ITC}(k,ij;l)X_{V4}(ij,k) + I^{FB}_{PFC-ITC},$$

$$X^{l}_{ITC} = \frac{1}{1+\exp\left(-\left(V^{l}_{ITC} - V^{th}_{ITC}\right)/\varepsilon_{ITC}\right)},$$

Network model of PFC

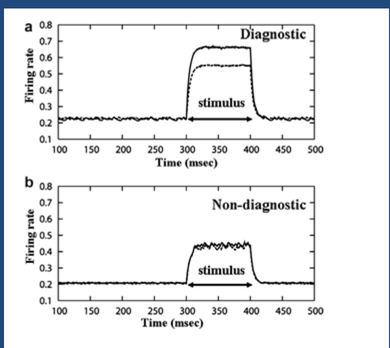


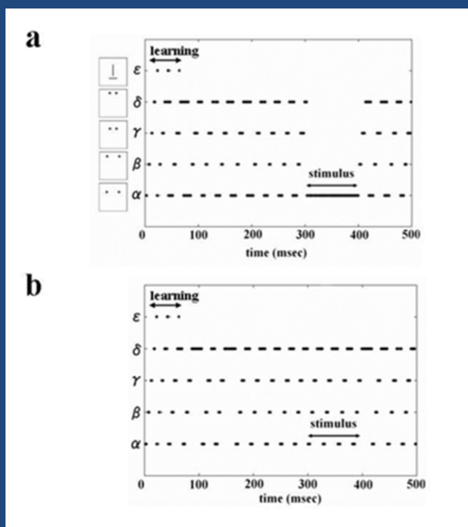
$$\tau_m \frac{du_m(ij;t)}{dt} = -u_m(ij;t) + \sum_{kl} \sum_{\tau^d_{ij,kl}=0}^{t_m} w_{mm}(ij;kl;t;\tau^d_{ij,kl}) X_m(kl;t-\tau^d_{ij,kl})$$
$$+ w_{mq} U_q(ij;t) + w_{mr} U_r(ij;t)$$
$$+ \sum_k w^{FF}_{ITC-PFC}(ij;k;t) X^k_{ITC}$$
$$+ \sum_{m,n} w^{FF}_{PP-PFC}(ij;mn;t) X^{mn}_{PP} + I^{FB}_{PFC-PM},$$

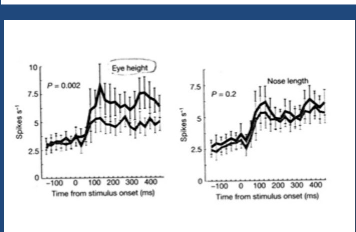
$$\tau_q \frac{du_q(ij;t)}{dt} = -u_q(ij;t) + w_{qm} X_m(ij,t),$$

$$\tau_r \frac{du_r(ij;t)}{dt} = --u_r(ij;t) + w_{rm} X_m(ij,t),$$

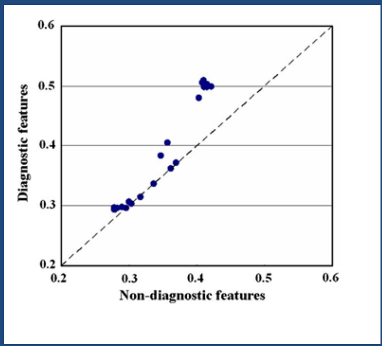
Responses of ITC and PFC neurons

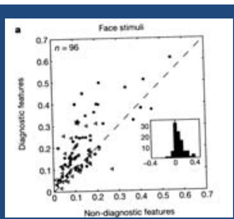


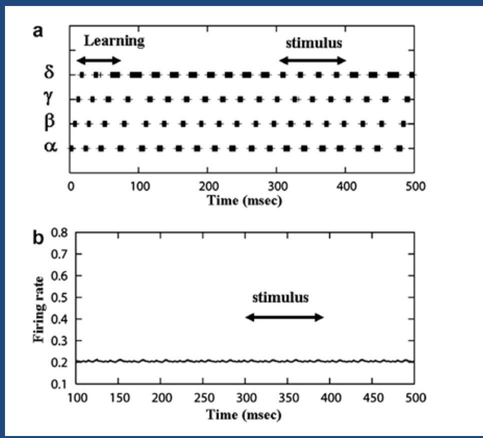




Response preference of ITC neurons for face features



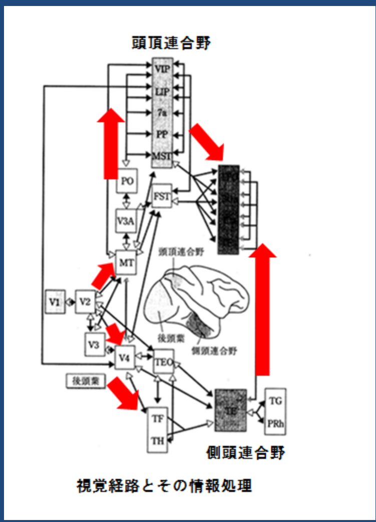


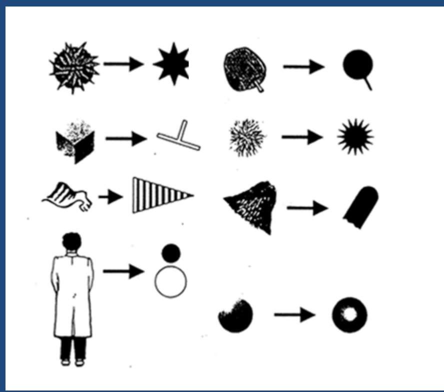


Response of the PFC network and of an ITC neuron induced by lesion of PP

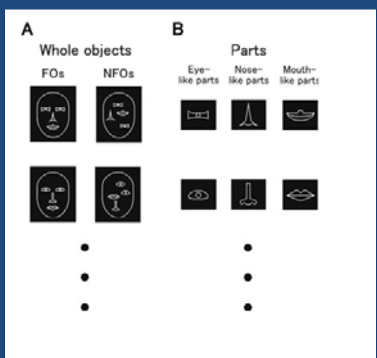
Neural mechanism of dynamic responses of neurons in inferior temporal cortex in face perception

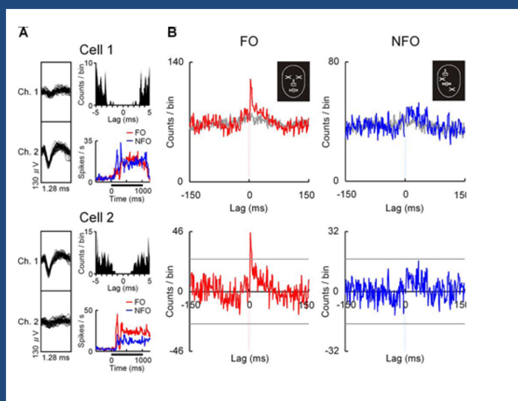
Hierarchical processing of face information in inferior temporal cortex





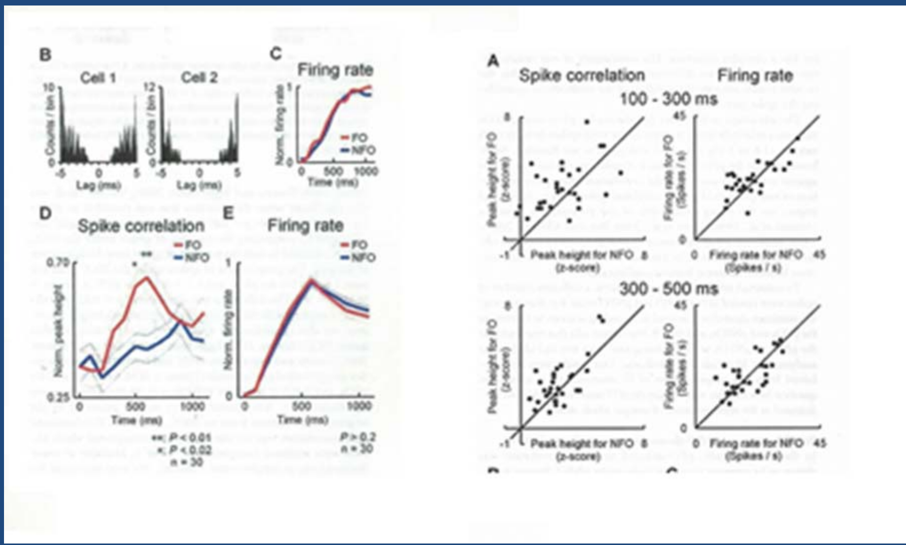
Highly correlated responses of IT neurons to face object





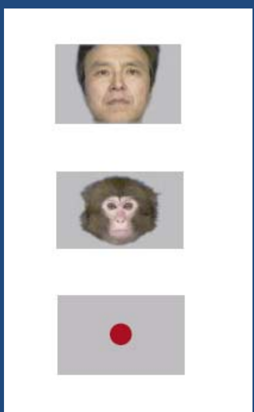
(Hiyabayashi and Miyashita, 2006)

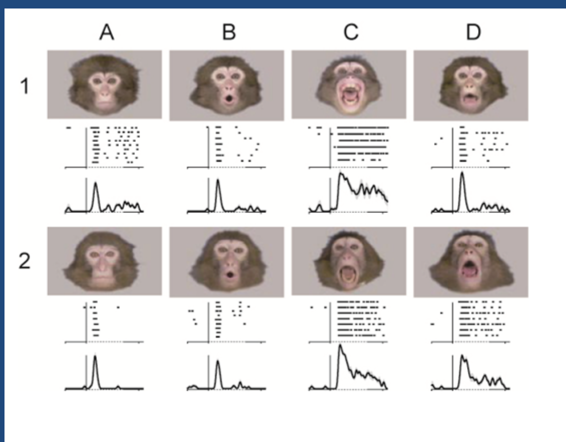
Temporal properties of spike correlations and firing rates



(Hiyabayashi and Miyashita, 2006)

Spike coding of global and fine features of face images

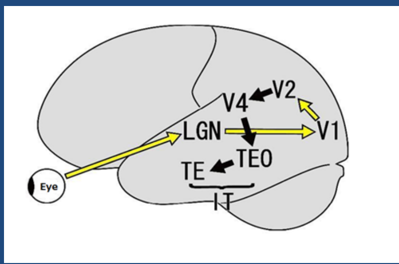




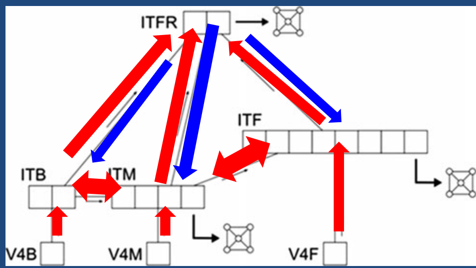
(Sugase et al., 1999)

Network model of hierarchical processing of face information

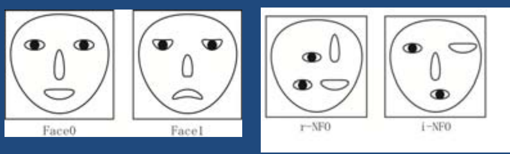
Ventral visual pathway



a whole image

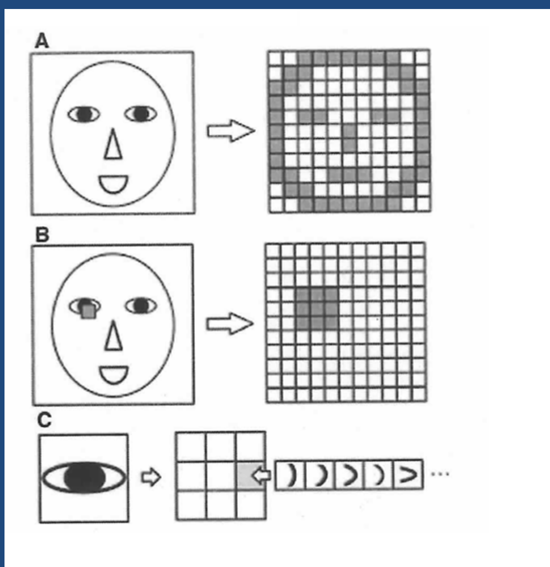


outline arrangement parts



(Yamada, and Kashimori, Cogn Neurodyn, 2013)

Coding of object features in V4 network



Equation of ITC neurons

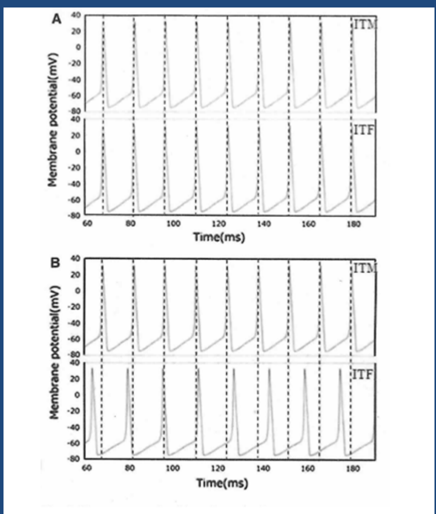
Membrane potentials of ith neuron in ITX layer (X=B,M,F)

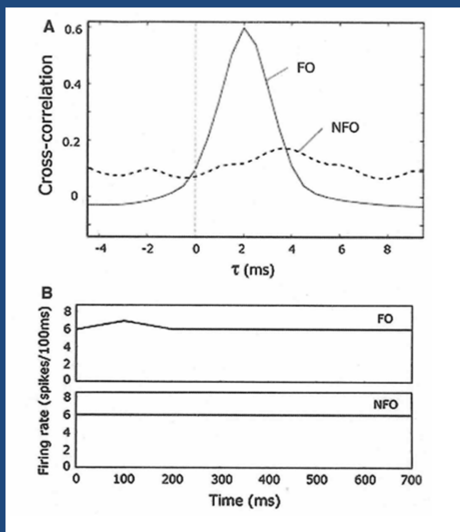
$$C_m \frac{dV_{i,ITX}}{dt} = -g_{Na} m^3 h (V_{i,ITX} - V_{Na}) - g_K n^4 (V_{i,ITX} - V_K) - g_L (V_{i,ITX} - V_L) + I_{FF} + I_{FB}$$

Synaptic weights between ith neuron in X layer and jth neuron in Y layer (X,Y=ITB,ITM,ITF, and FRL)

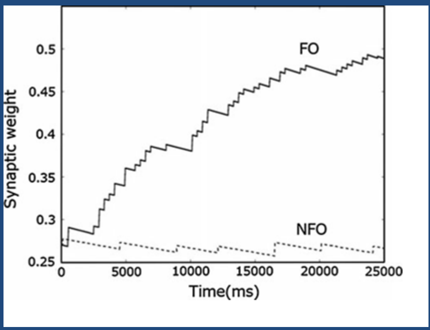
$$\tau_w \frac{dw^Z_{ij,XY}}{dt} = -w^Z_{ij,XY} + \eta S_{iX} S_{jY}$$

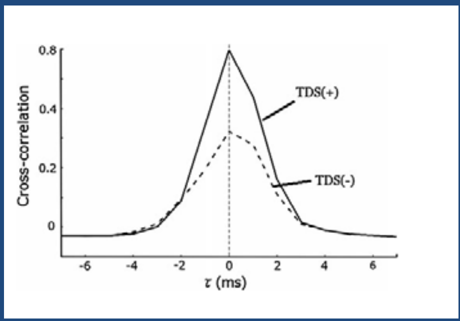
Response properties for a pair of ITF neurons encoding the features of eye and nose



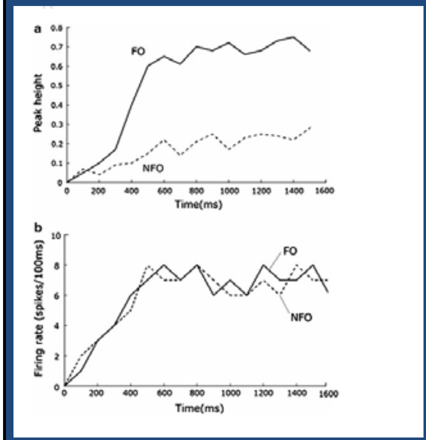


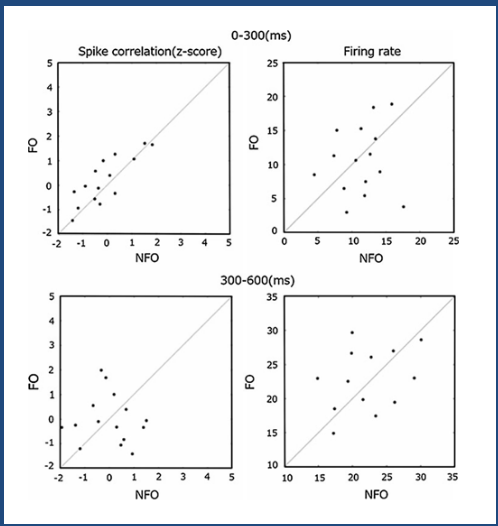
Effect of top-down signal on spike correlation of a pair of IT neurons



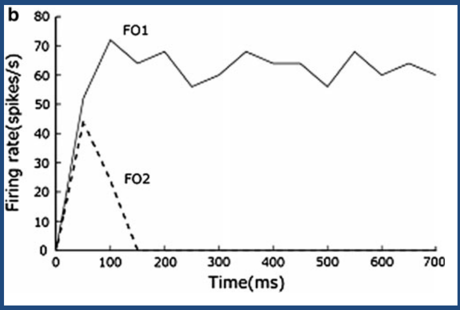


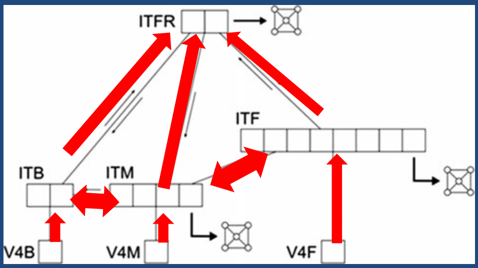
Calculated results





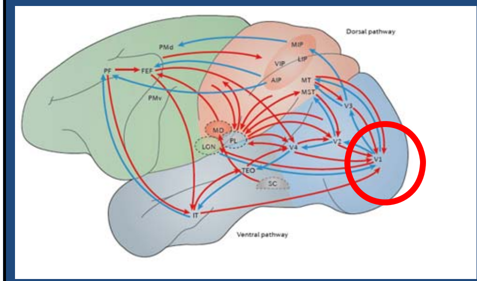
Coarse-to-fine process





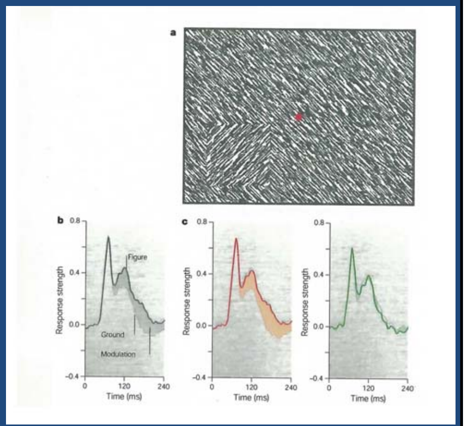
Top-down influence on V1 responses in perceptual learning

Top-down influence on V1 responses in perceptual learning



(Gilbert and Li, 2013)

Li et al. 2004
Ramalingam et al. 2013
Li et al. 2006
Gilbert and Sigman ,2007
Tong, 2003

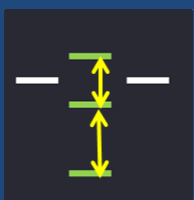


(Super et al., 2001)

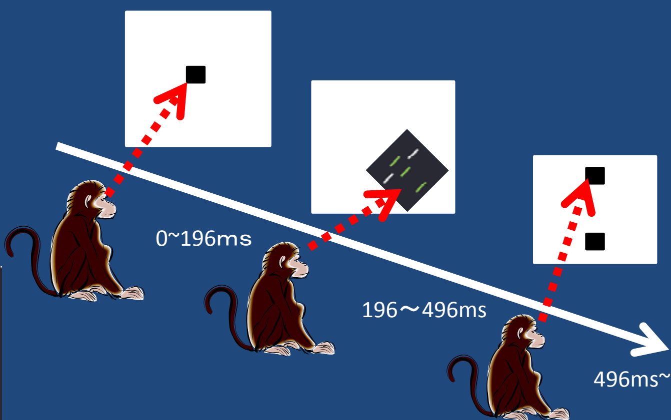
66

Five-bar discrimination task

Bisection task



Vernier task



(Li et al. 2004)

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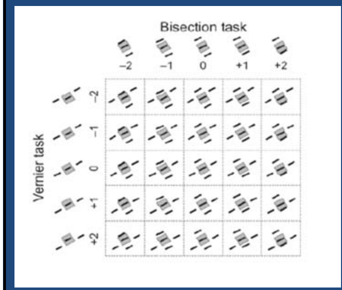
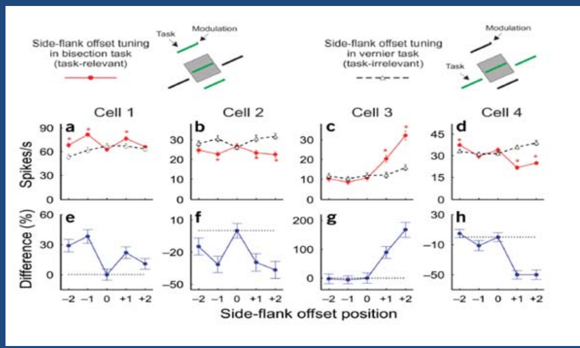
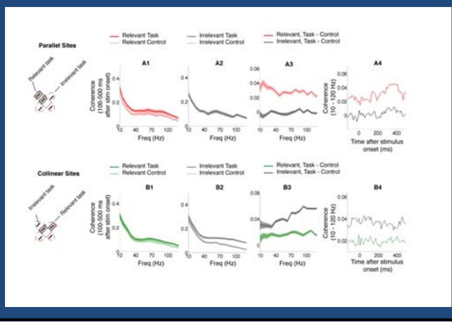




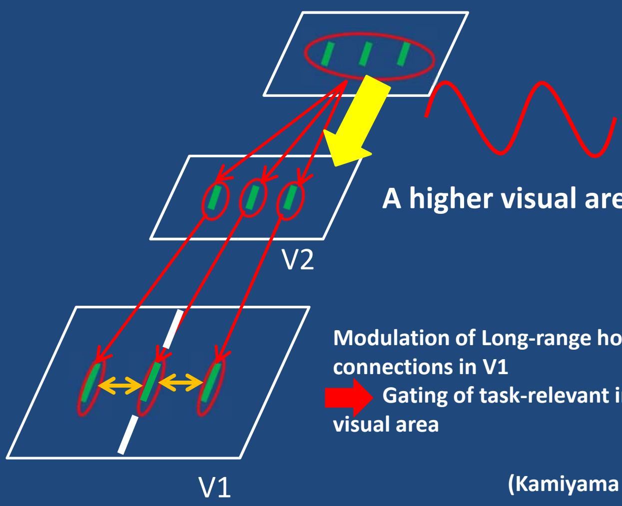


(Li et al. 2004)

Our approach

Top-down influence reflecting
perceptual strategies of the two tasks

Synchronous oscillation
(Bisection task)
Asynchronous oscillation
(Vernier task)

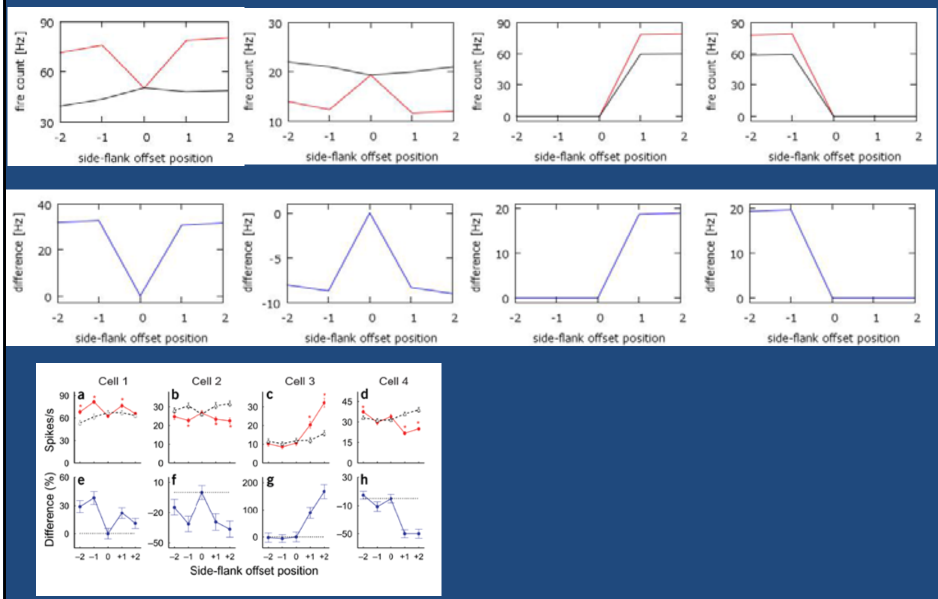


A higher visual area (V2)

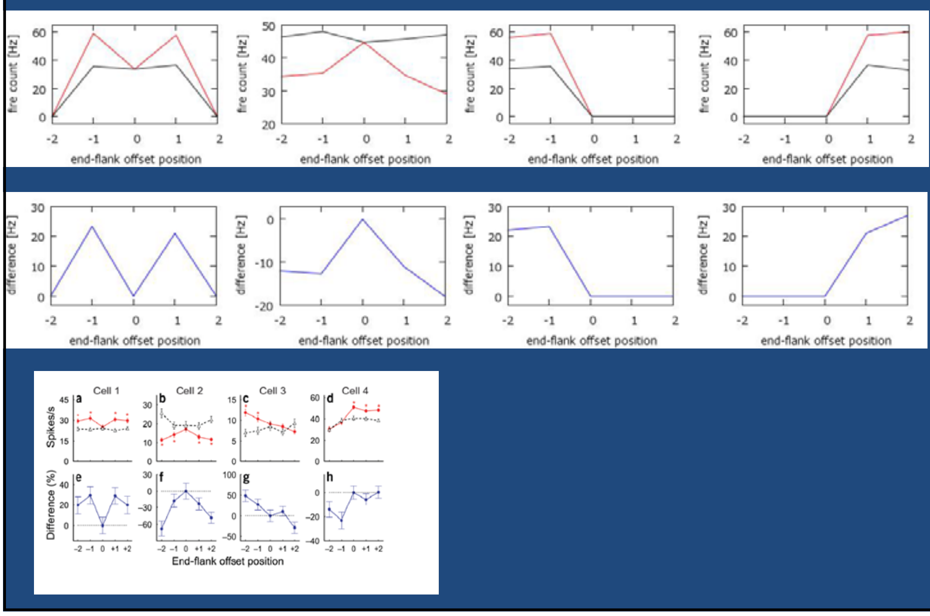
Modulation of Long-range horizontal connections in V1
➡ Gating of task-relevant information in early visual area

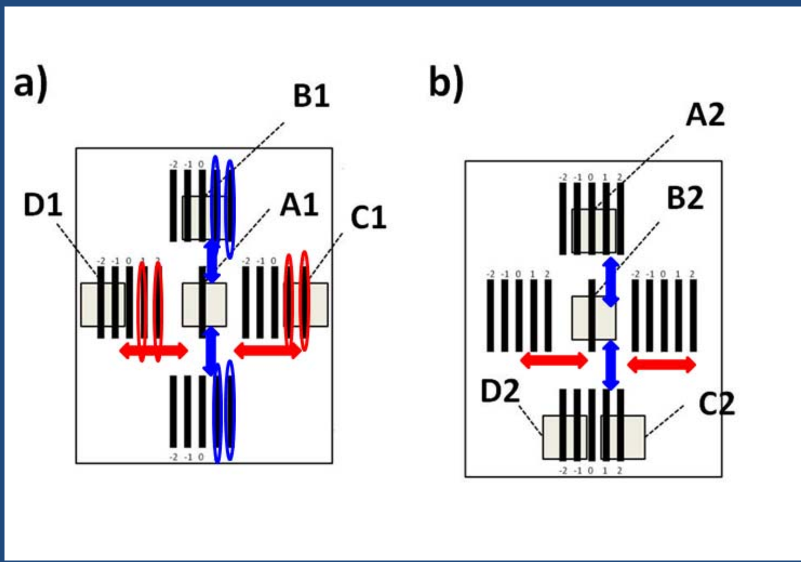
(Kamiyama et al., to be published)

Bisection task

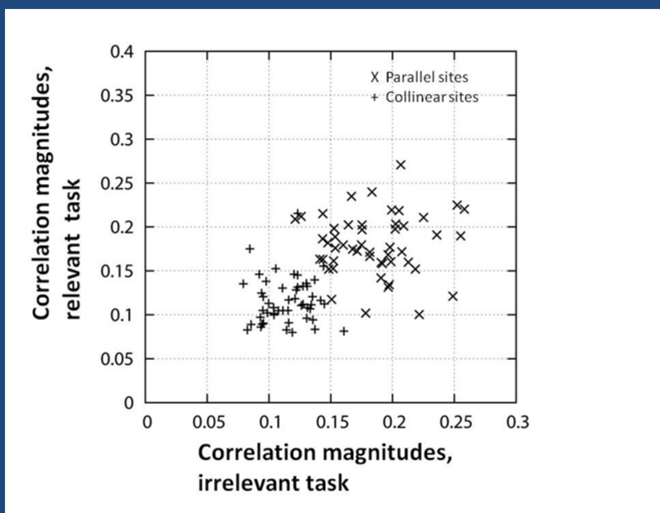


vernier task





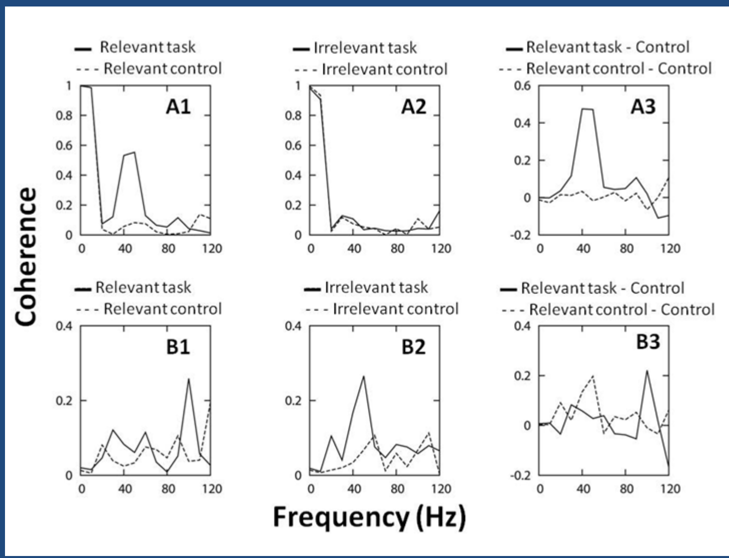
Spike correlations



LFP coherence

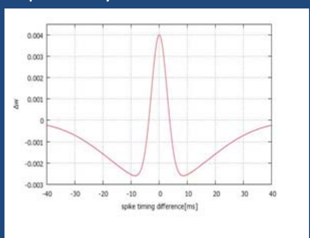
Bisection task

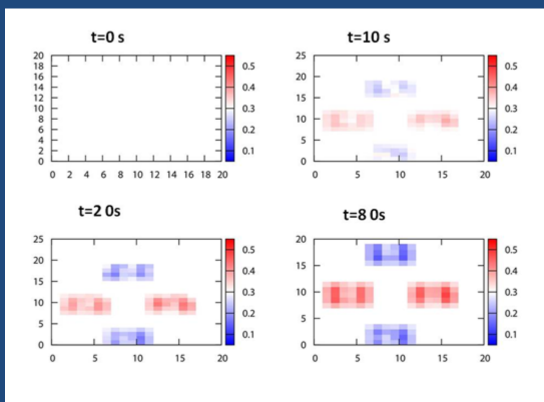
Verinier task

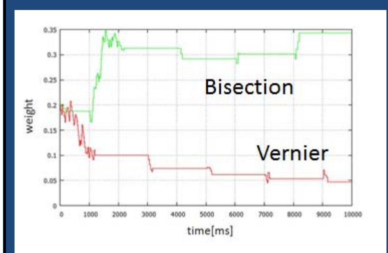


Formation of functional connectivity in the V1 network

Spike-timing dependent plasticity

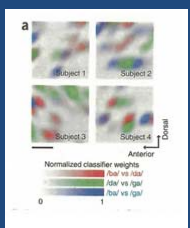




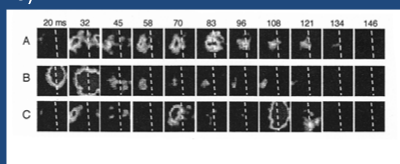


Decoding Word Information from Spatiotemporal Activity of Sensory Neurons

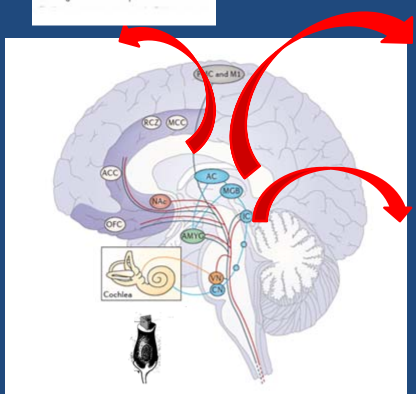
Hierarchical processing of auditory information

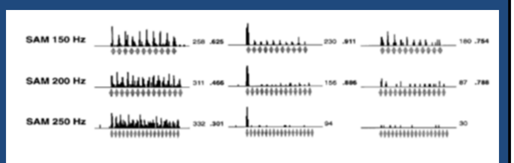


pSTG
(Chang et al., 2010)



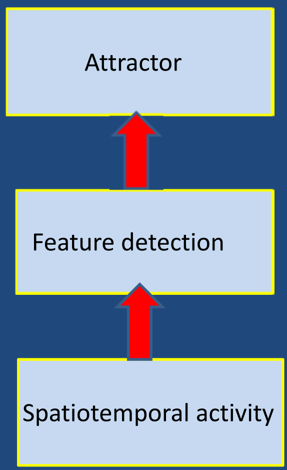
(Horikawa et al. 1996)

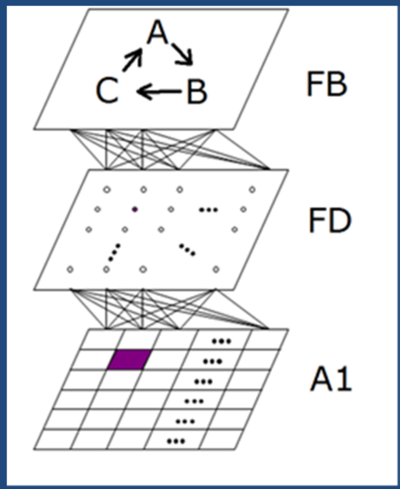




(Burger and Pollak, 1998)

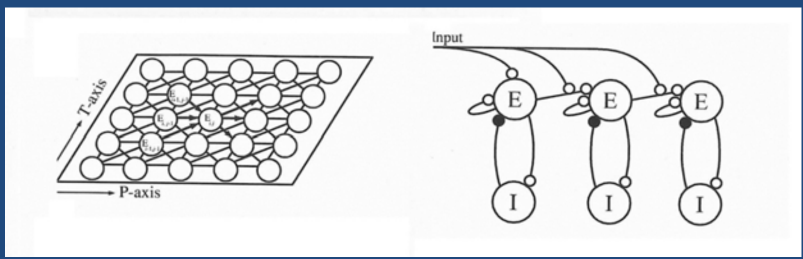
Model

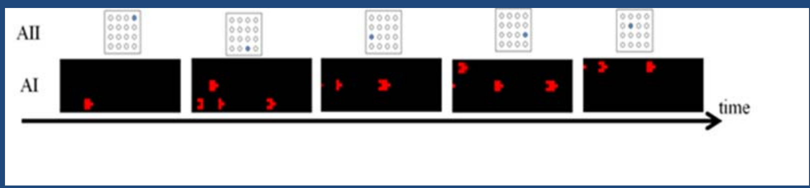




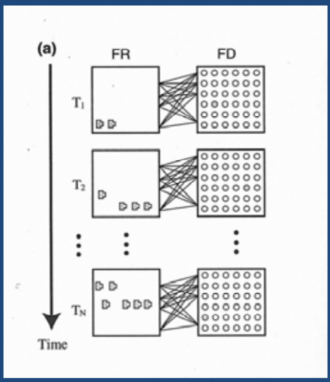
(Hara et al., Cog Comput, 2014)

The model of A1

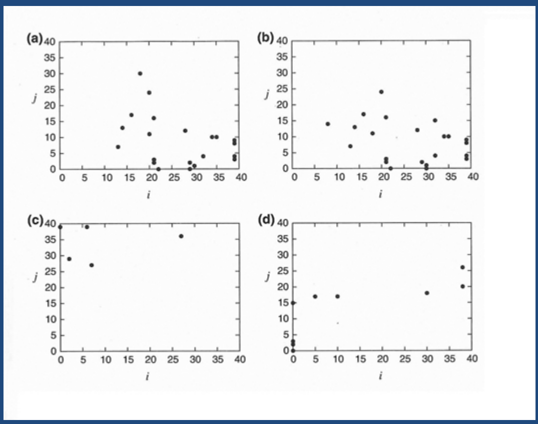




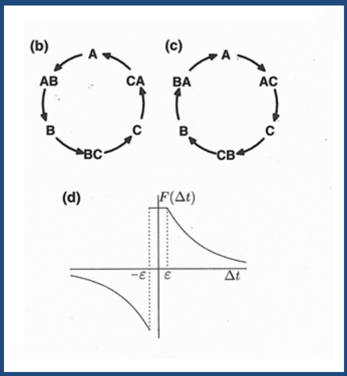
Model of FD layer

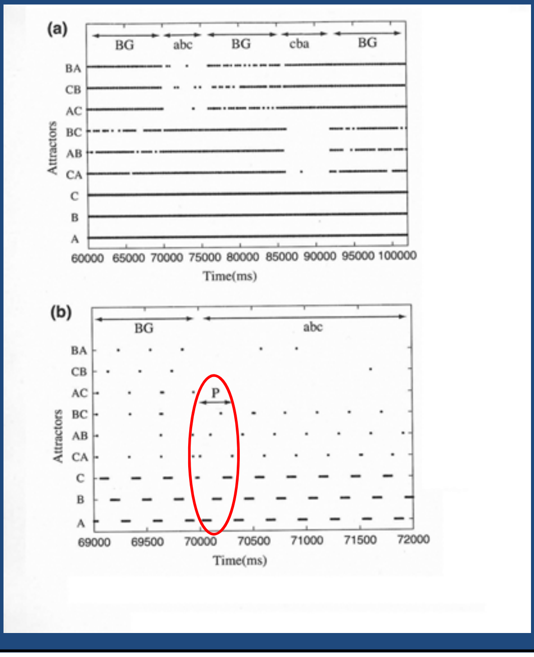


Responses of FD neurons



Model of FB layer

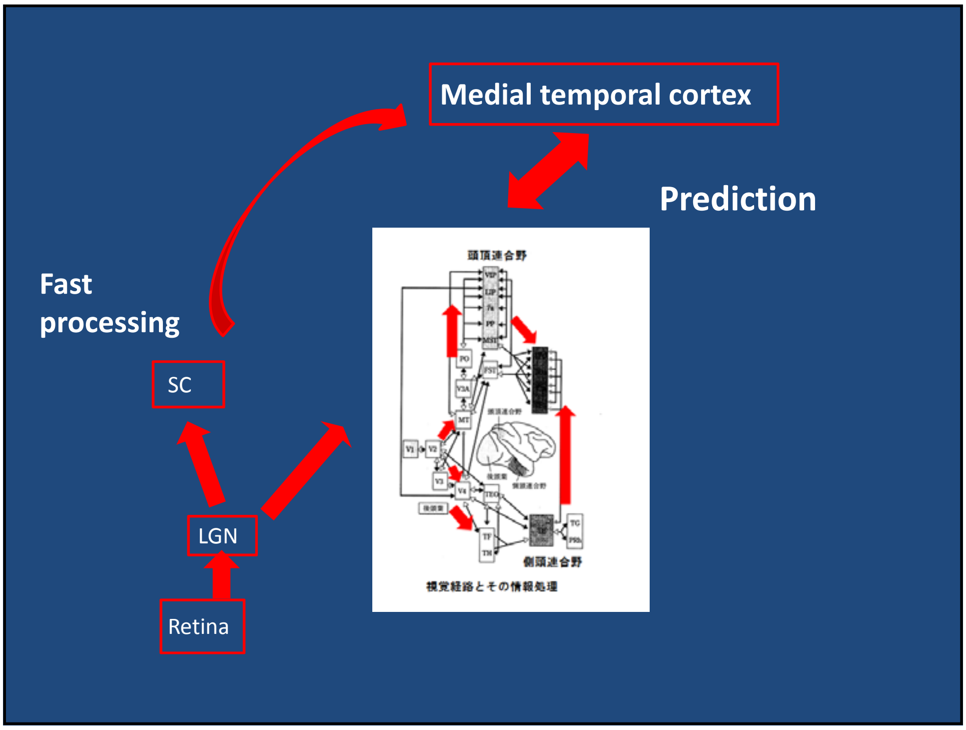




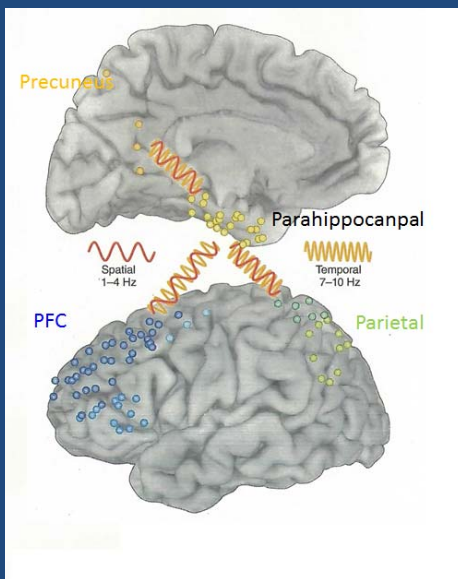
Attractor models

- Olfactory system
- Visual system
  categorization, face perception, top-down influence
- Auditory system
  word perception, information processing in A1
- Gustatory system,
  interaction between odor and gustatory information
- Somatosensory system (tactile, haptic)

Future work



Communication between brain areas through different rhythms



(Watrous et al., 2013)