第 11 回人間福祉テクノロジー研究ステーションセミナー (2012.03.16)

# 視覚野カラムの形態と可塑性に関する研究

企画調査室　特任教授

田中　繁

## 自己紹介／研究歴

1981–1983 表面物性の理論　（東京大学物性研、修士課程）
1983–1986 金属微粒子の理論（東京大学物性研、博士課程）

1986–1994 視覚野マップ自己組織化（NEC基礎研究所）
1994–1997 視覚野マップのトポロジー（理研国際フロンティア研究システム）

1997–2009 視覚・聴覚野マップの光学計測
視覚野の発達研究、小脳の内部時計モデル
三次元視覚野のfMRI計測とモデ
スパイクタイミング依存シナプス可塑性のモデル
（理研脳科学総合研究センター）

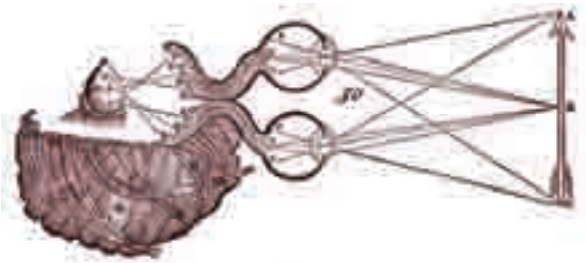
2009–2012 大脳皮質–基底核のモデル化とワーキングメモリ
（電通大）

## 本日お話する主な内容

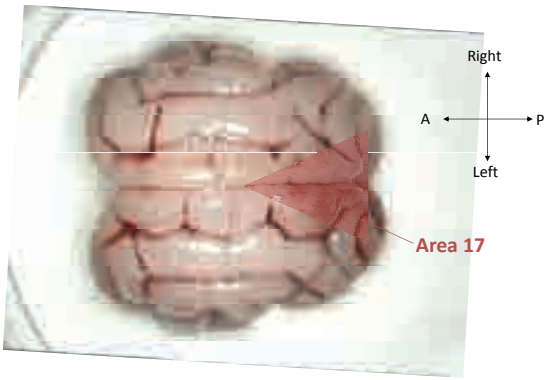
- 視覚野方位マップの形態：内因性光学計測実験
- 視覚野マップのトポロジー：ホモトピー論
- 視覚野マップ/カラムの再現：自己組織化理論
- 視覚野カラムの3次元的再構成：fMRI実験
- 視体験による方位マップの再編：理論・実験
- 最近の研究

# Introduction

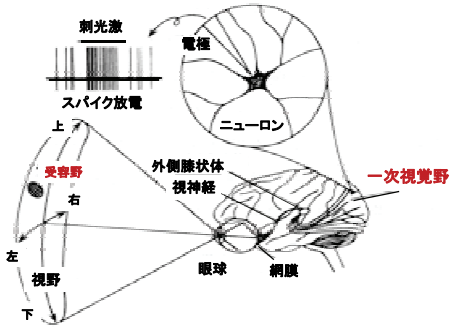
## デカルト的描像



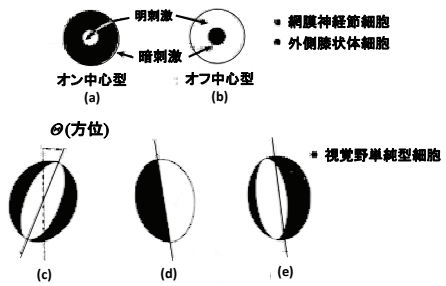
## Cat cerebral cortex



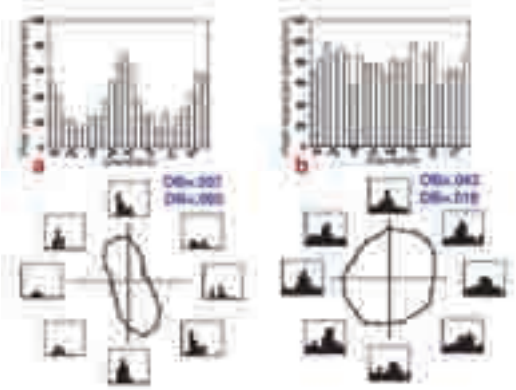

## Electrophysiology



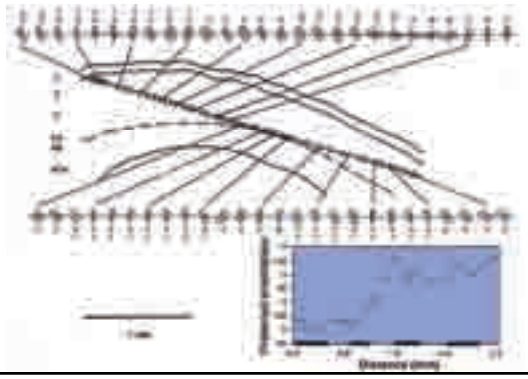
## Receptive fields



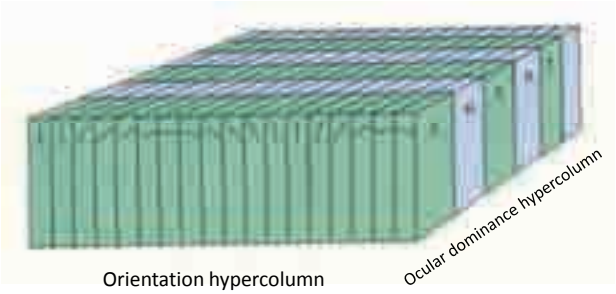

## Tuning curves & polar plots



## Preferred orientations along electrode track

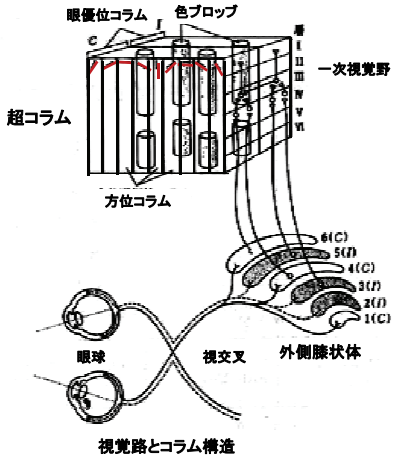


## Hubel & Wiesel's ice-cube model




## Revision of hypercolumn model

Preferred orientations are arranged in a pinwheel-like structure (Bonhoeffer & Grinvald, Nature 1991).

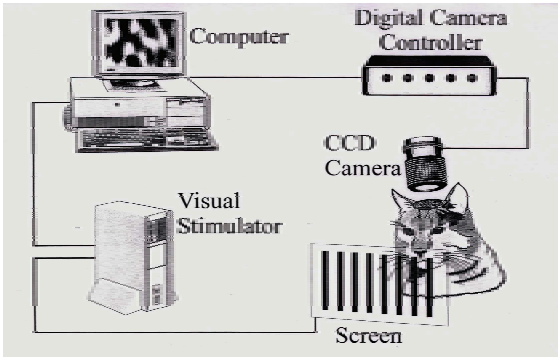



視覚路とコラム構造

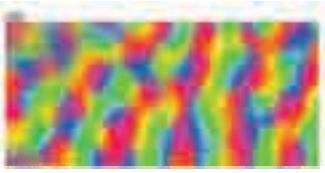
# 視覚野方位マップの形態

# 内因性光学計測実験

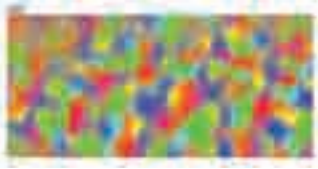
## Optical imaging setup




## Functional maps in cat visual cortex

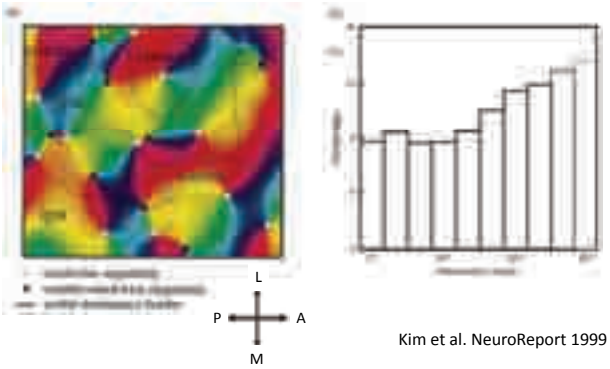


Orientation map



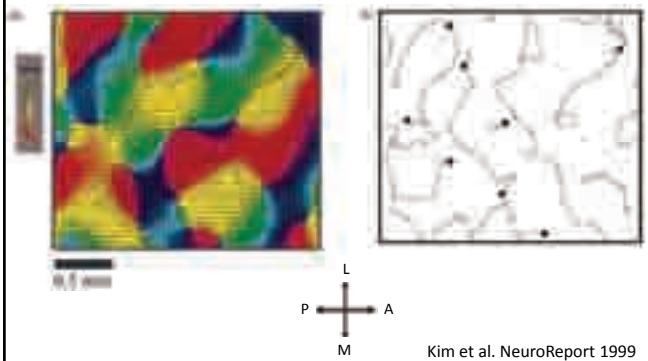
Direction map

## Orientation-ocular dominance joint maps




Kim et al. NeuroReport 1999

## Orientation-direction joint maps



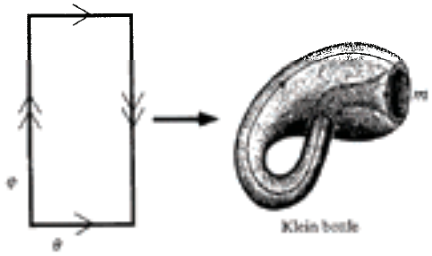

Kim et al. NeuroReport 1999

# 視覚野マップのトポロジー

# ホモトピー論

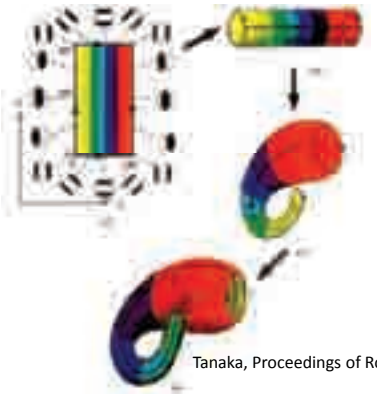
## トポロジー理論：マップの特異性

Simple cell receptive field $R(\vec{x}) = A\exp\left[-\frac{(\vec{x}-\vec{X})^2}{2\sigma^2}\right]\cos\left[2\pi\vec{\omega}(\theta)\cdot(\vec{x}-\vec{X})-\phi\right]$




Tanaka, Proceedings of Royal Society Lond. B 1995

## Equivalence between feature space & Klein bottle



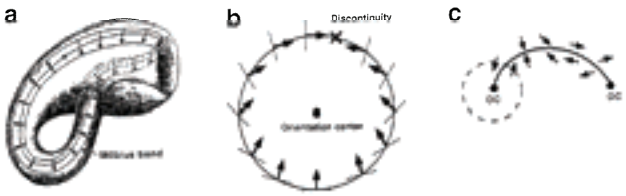
Tanaka, Proceedings of Royal Society Lond. B 1995

## Point-redusibility of loops & orientation singularities

Tanaka, Proceedings of Royal Society Lond. B 1995

## 方位選択性の特異点と方向選択性の不連続線の幾何学的関係

Fundamental group of visual features $\pi_1(S) = \pi_1\left(K^2 \otimes D^2\right) = \pi_1\left(K^2\right) \otimes \pi_1\left(D^2\right) = \pi_1\left(K^2\right) = Z \otimes Z_2$




Tanaka FORMA 1997

## 視覚野マップ/カラムの再現

## 自己組織化理論

## マップ構造の自己組織化理論

- Hebbian synapse
  NMDA receptorの電位依存的な$Ca^{2+}$の流入
- Synaptic constraint
- Lateral excitation/inhibition
- Modifiable afferent input synapses

(Tanaka Neural Networks 1990)

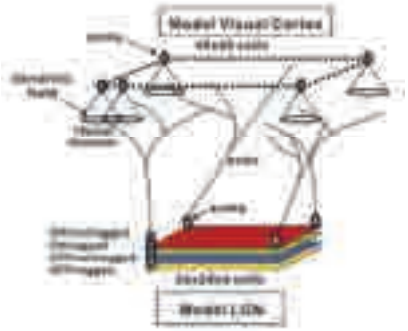
→ ①「類は友を呼ぶ」原理
②「勝者一人占めの原理」（winner-take-all）

～磁性薄膜のドメイン構造、ベナール対流（OD）

(Tanaka, Human & Machine Perception 1992)

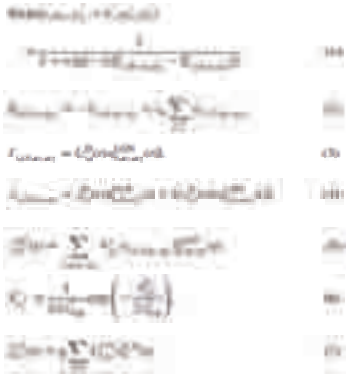
～液晶における回位（OR pinwheel centers）

## Self-organization model

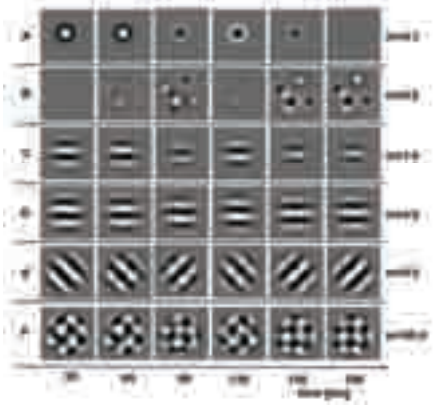


Tanaka et al. 2004 Neural Networks 2004

## Mathematical description



## Self-organized receptive fields



Tanaka & Miyashita Neural Comput. 2009

## Spatio-temporal receptive fields of model cortical neurons

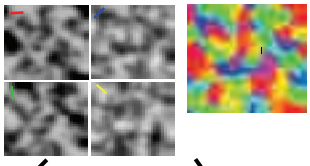
Fluctuation term only

Systematic term only

Miyashita et al. NeuroReport 1997

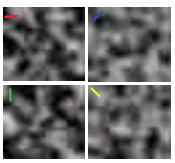
## Visual experience & synaptic gating

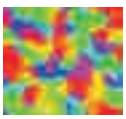
Spontaneous activity



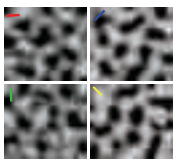


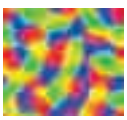
Visual instruction





Visual instruction + gating





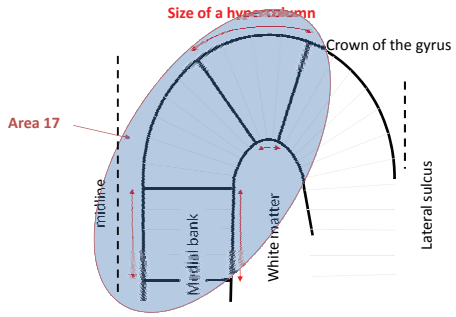
Quite similar to OR maps in cat area 17

宮下 & 田中　電子情報通信学会論文誌D 2006

## Curvature of cat visual cortex

## How does orientation representation look like around the crown of the gyrus?

According to Hubel & Wiesel's idea

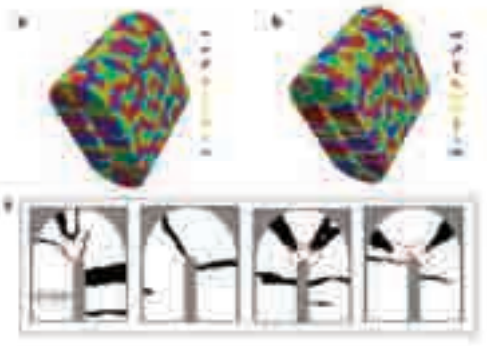



## Self-organization of visual feature representation in 3-D cortex

(1) Orientation, direction, ocular dominance and retinotopy are taken into account.
(2) Correlation-based learning is employed.
(3) Isotropic cortical interaction is assumed.
(4) 5-layer structure is assumed
(5) Simulation rage gradually expands from the middle layer (spatial annealing).

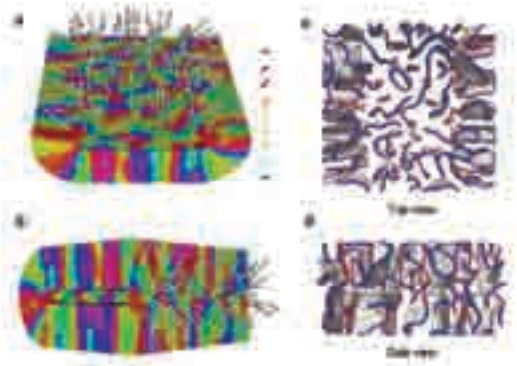
Tanaka et al. Neural Networks 2011

## Orientation & direction representations



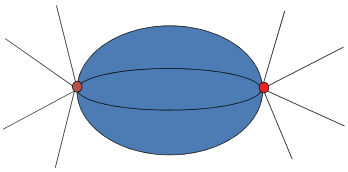
Tanaka et al. Neural Networks 2011

## Orientation & direction singularities



Tanaka et al. Neural Networks 2011

## Why do hairpin-like orientation singularity lines appear?



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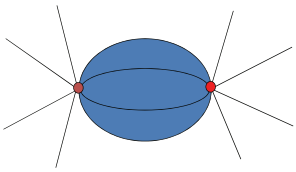

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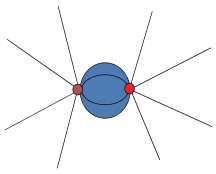

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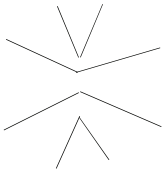
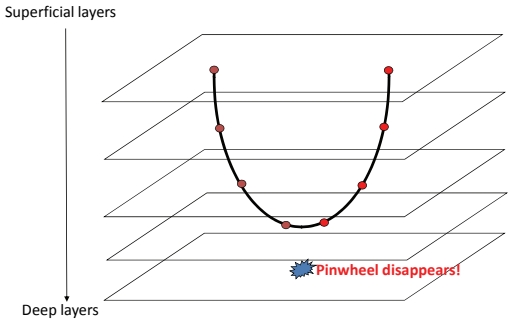
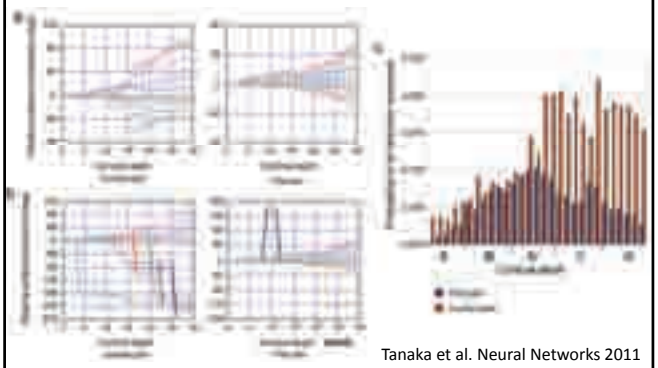


**Pair annihilation!**

## Pair annihilation of pinwheel centers

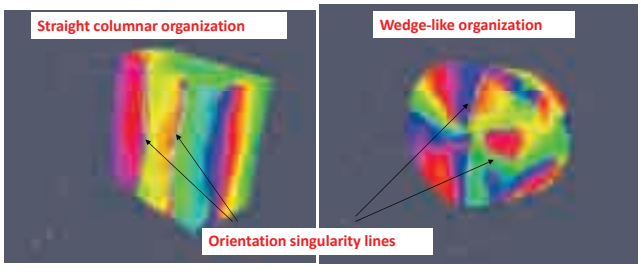



## Changes in preferred orientation & direction in the cortical depth



Tanaka et al. Neural Networks 2011

## 3D orientation representation & line singularities




Model flat cortex  Model curved cortex

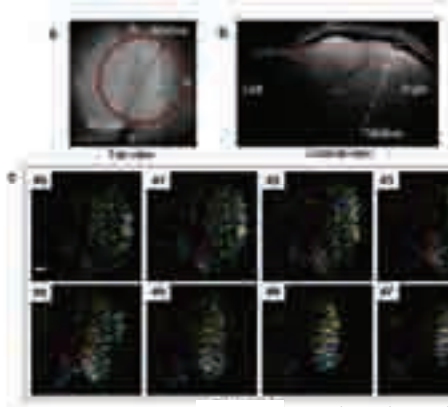
## Mechanisms

- Preferred orientation tends to be represented in a periodic manner.
- Similar preferred orientation tends to be aligned along the depth direction.
- Orientation representation is determined by the balance/competition between the two tendencies.

# 視覚野カラムの3次元的再構成

fMRI実験

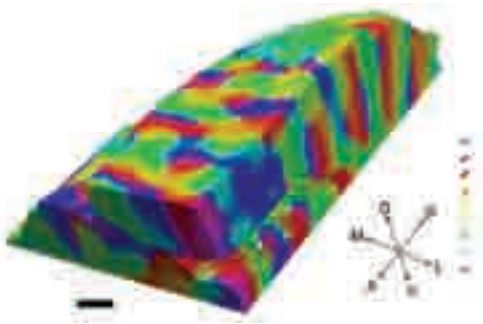
## Confirmation by fMRI study



9.4T
Injection of monocrystalline iron oxide nanoparticles (MION)

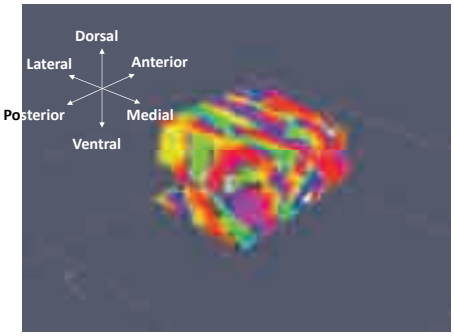
Tanaka et al. Neural Networks 2011

## 3-D reconstruction of orientation representation



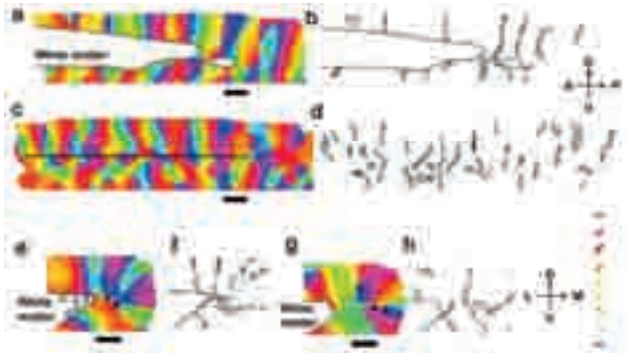
Tanaka et al. Neural Networks 2011

## 3D orientation representation & line singularities reconstructed by fMRI




**Orientations are not necessarily represented in a columnar fashion!!!**

## Orientation representations in different cross sections

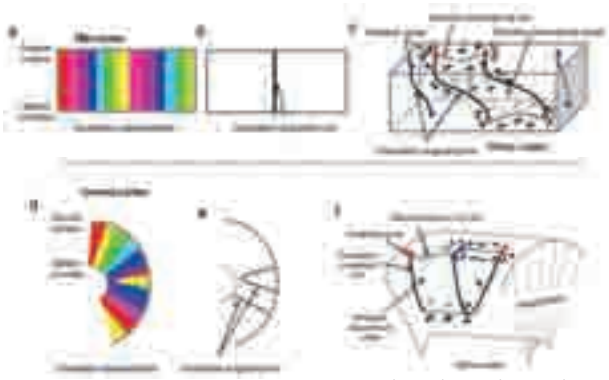


Tanaka et al. Neural Networks 2011

## Single-orientation domains in coronal & saggital sections

Tanaka et al. Neural Networks 2011

## Schematic diagrams of orientation & direction singularities



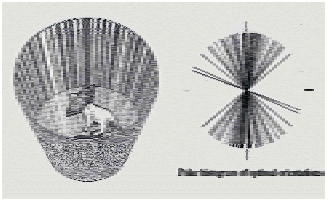
Tanaka et al. Neural Networks 2011

# 視体験による方位マップの再編

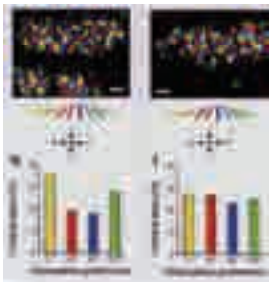
理論・実験

## 視体験による方位マップの再編

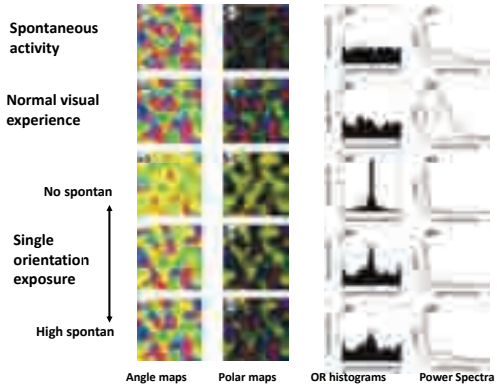
**Blakemore & Cooper (1970)**
**Visual experience is crucial for orientation selectivity formation.**



**Sengpiel, et al. (1999)**
**Basic structure of orientation maps is robust against visual experience.**

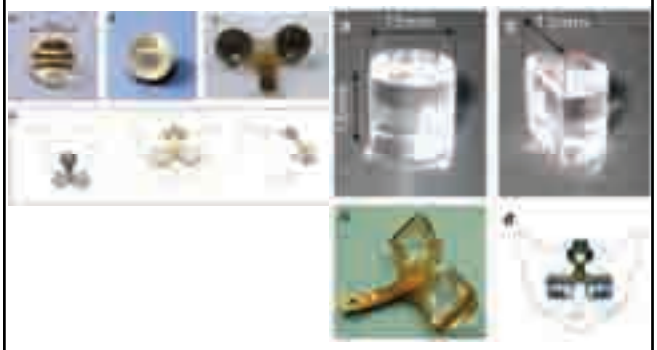


## Simulated orientation maps under different visual conditions



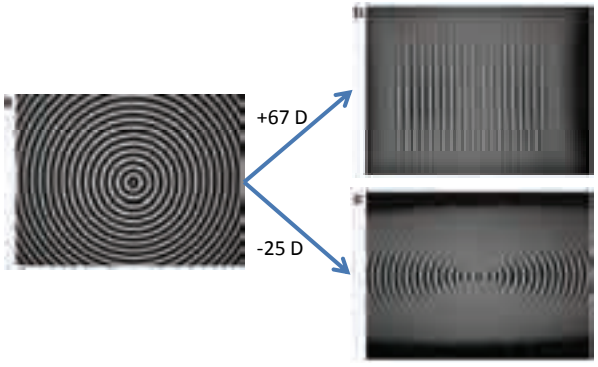

Tanaka et al. Neural Networks 2004

## Gogglesを用いた視体験操作



Tanaka et al. J. Neurosci. Methods 2007

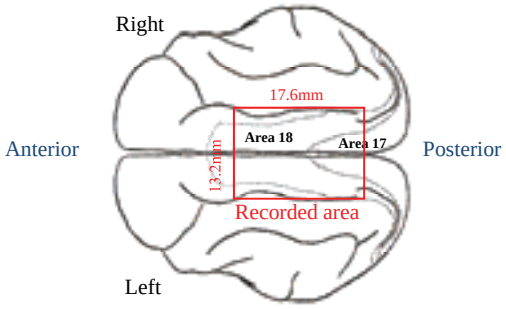
## Deformed view of concentric circles through cylindrical lenses



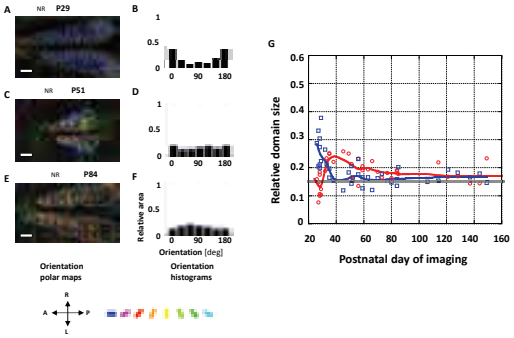
## Movies of goggle-mounted kittens

1. In the animal cage
2. Eating
3. Playing with a ball
4. Playing with a mop

## Cat Visual Cortex: Areas 17 and 18

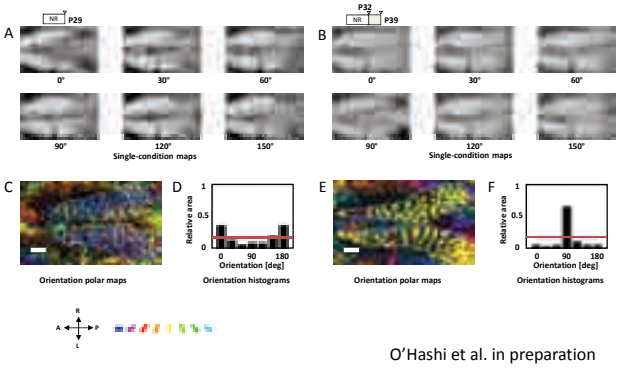



## 正常飼育ネコの実験結果



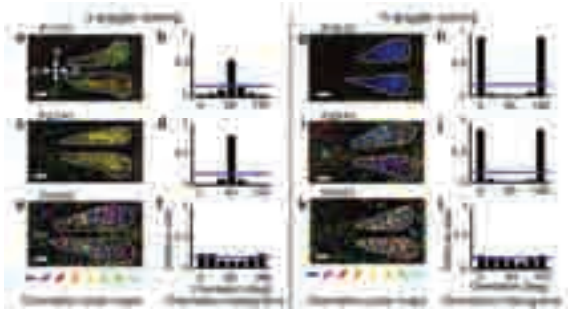

Tanaka et al. PLoS ONE 2009

## 縦縞飼育による方位マップの再編



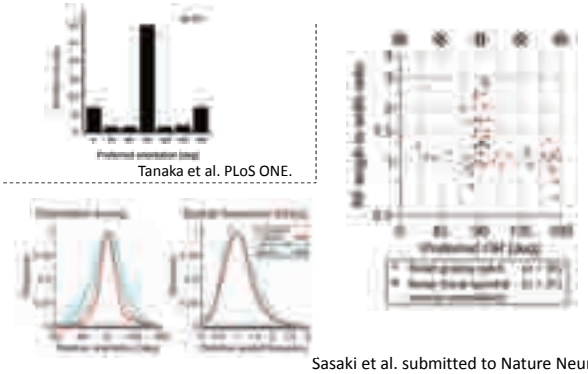

O'Hashi et al. in preparation

## 視体験による方位マップの再編



Tanaka et al. PLoS ONE 2009

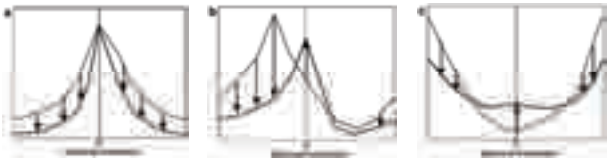
## Unit recording of visual cortical neurons in goggle-reared cats



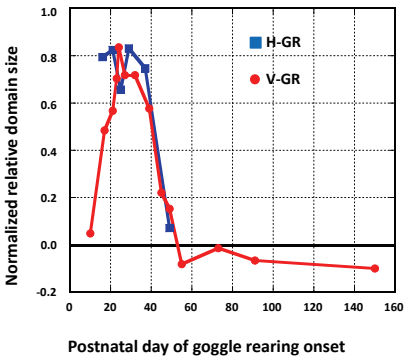
Tanaka et al. PLoS ONE.

Sasaki et al. submitted to Nature Neurosci.

## Supposed changes of tuning curves by single-orientation exposure

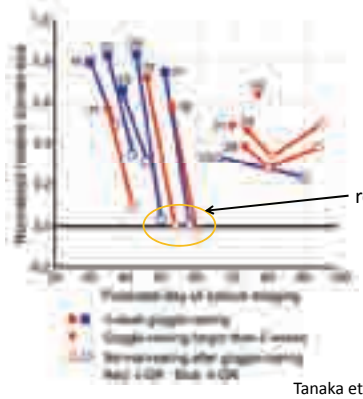


## Sensitivity profile of orientation plasticity




Tanaka et al. PLoS ONE 2009

## Recovery effect from goggle rearing

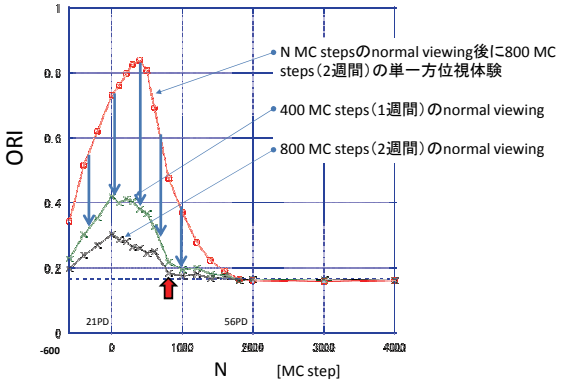



Tanaka et al. PLoS ONE 2009

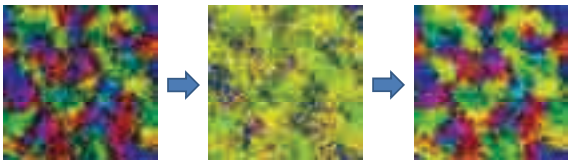
## Recovery effect by normal viewing

Normal rearing　1-w goggle rearing　1-w normal viewing

## Simulated sensitivity profile of orientation plasticity

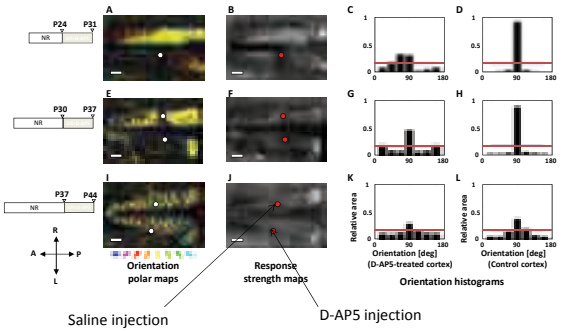



## Simulation of recovery effect



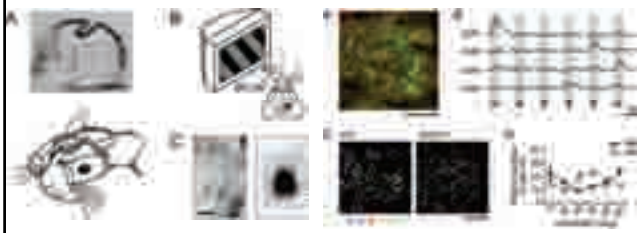
400ステップ正常飼育　800ステップ単一方位飼育　800ステップリカバー

## NMDAR involvement in orientation plasticity

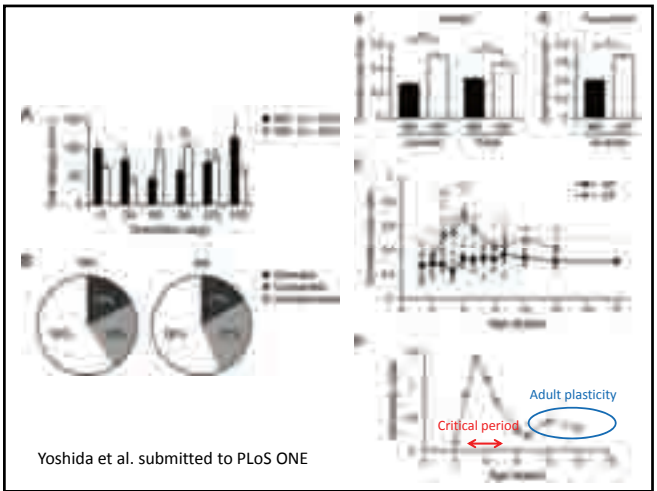



Tanaka et al. PLoS ONE 2009

## マウス視覚野における 2光子励起カルシウムイメージング



Yoshida et al. submitted to PLoS ONE




Yoshida et al. submitted to PLoS ONE

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**Data analysis**
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**D-AP5 injection**
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Katsuya Ozawa

**fMRI recording in cats**
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Chang-Hong Moon
Mitsuhiro Fukuda

## 物質としての脳から過程としての心へ

What is mind? – It's not matter.
What is matter? – Don't mind.

○まず、物質としての脳について理解を深める。
解剖学的構造、生理学的特性、機能性分子・伝達物質の性質、イメージング技術、回路網理論
○次に、精神過程について学ぶ。
認知心理学的知見：知覚、注意、記憶、学習、動機、予測、欲求、運動、プランニング、意識、 etc.

# 最近の研究