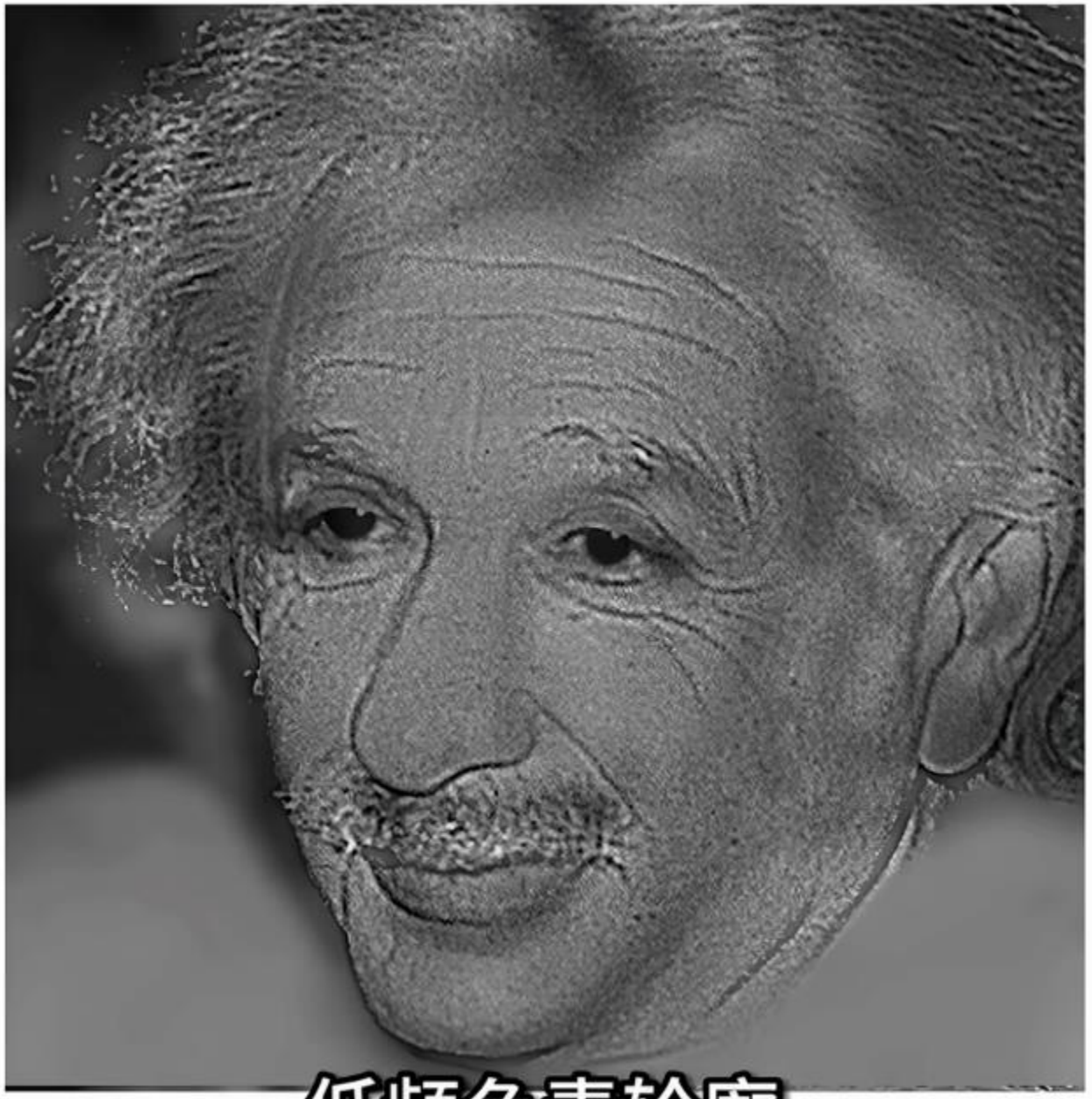
How Do We See the World?

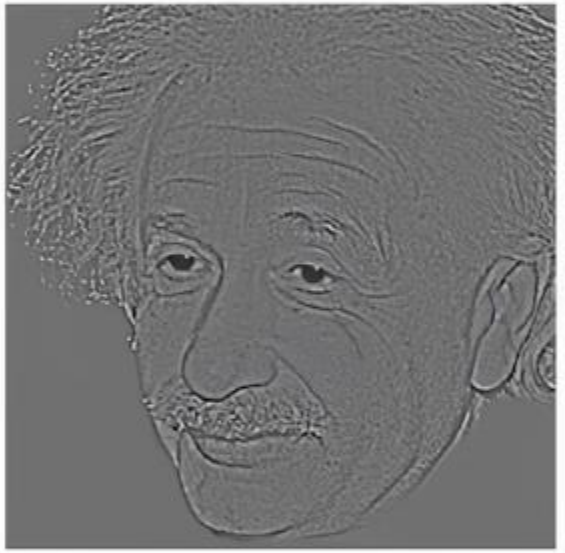
From Visual Neuroscience to Future Vision

低频





高频



低频负责轮廓

How Do We See the World?

From Visual Neuroscience to Future Vision

Part I: How Do We See? From Light to the Brain

------LXL

Part II: When Vision Fails: Can We Restore Sight?

------WYJ

Part III: Can We Engineer Vision?

------CDL

JOURNAL CLUB • PART I

How Do We See? From Light to the Brain

LXL

2026.09.24

THREE QUESTIONS

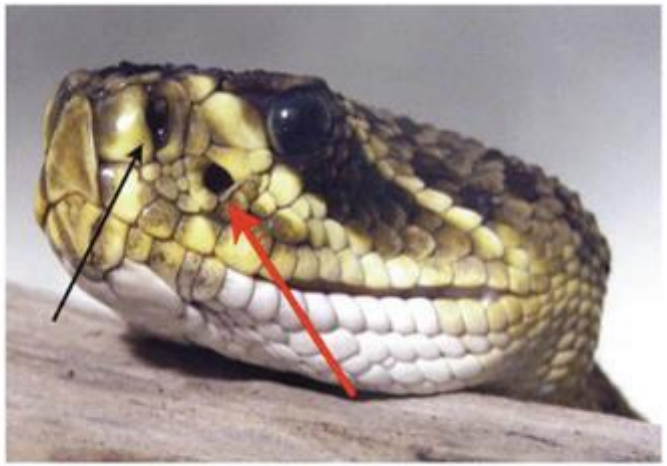
01 What can be sensed?

02 What does the retina compute?

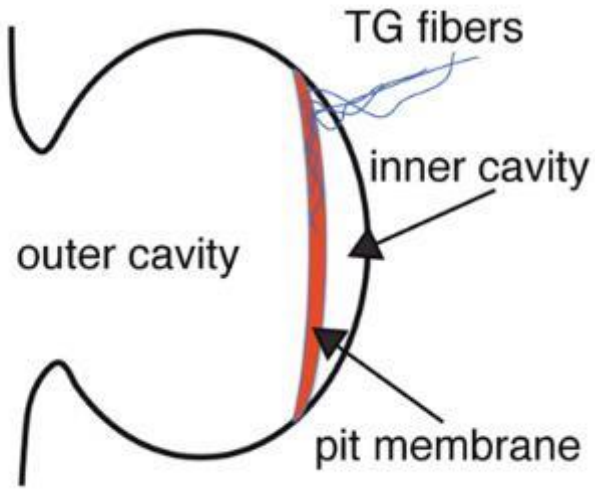
03 How does neural activity become perception?

Infrared Sensing in Snakes

a



b



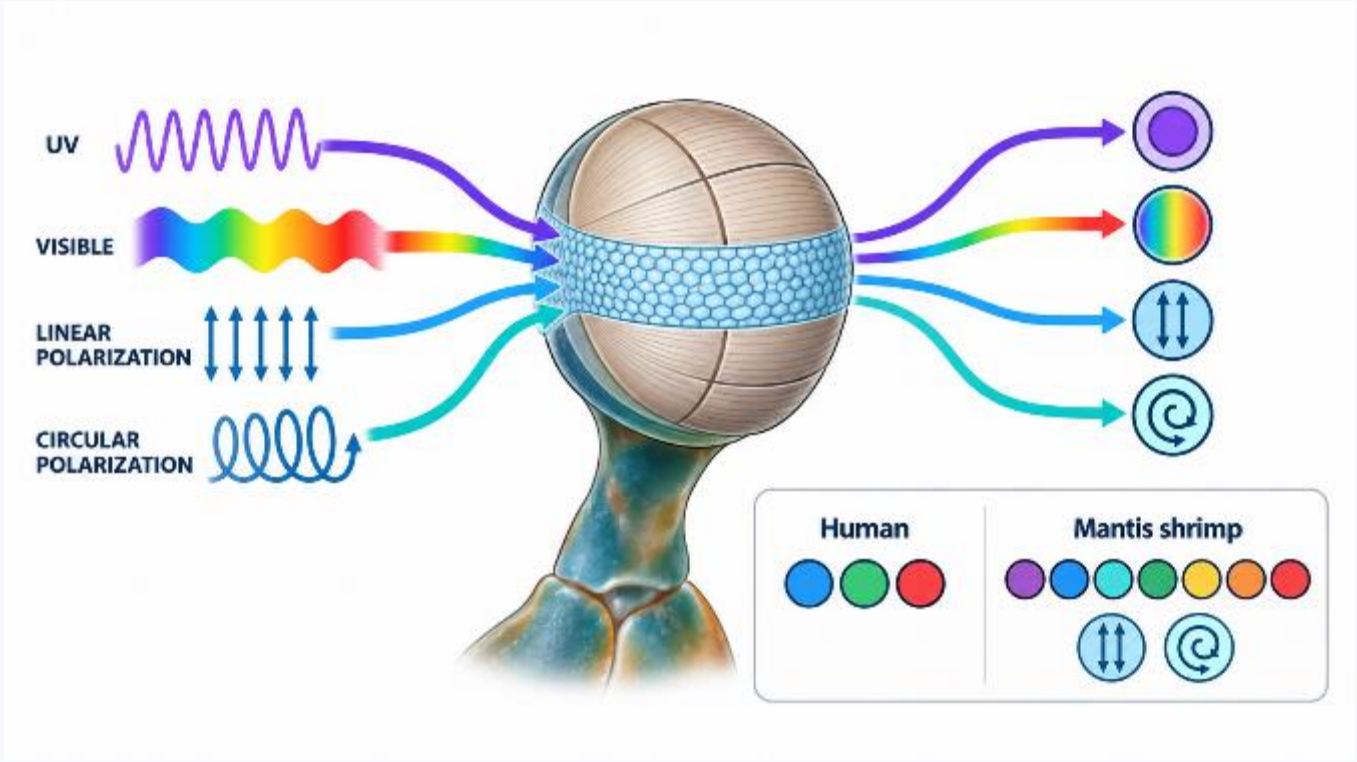
IR radiation heats pit membrane

TRPA1

Gracheva EO et al. Nature. 2010. doi:10.1038/nature08943

Visual Dimensions of Mantis Shrimp

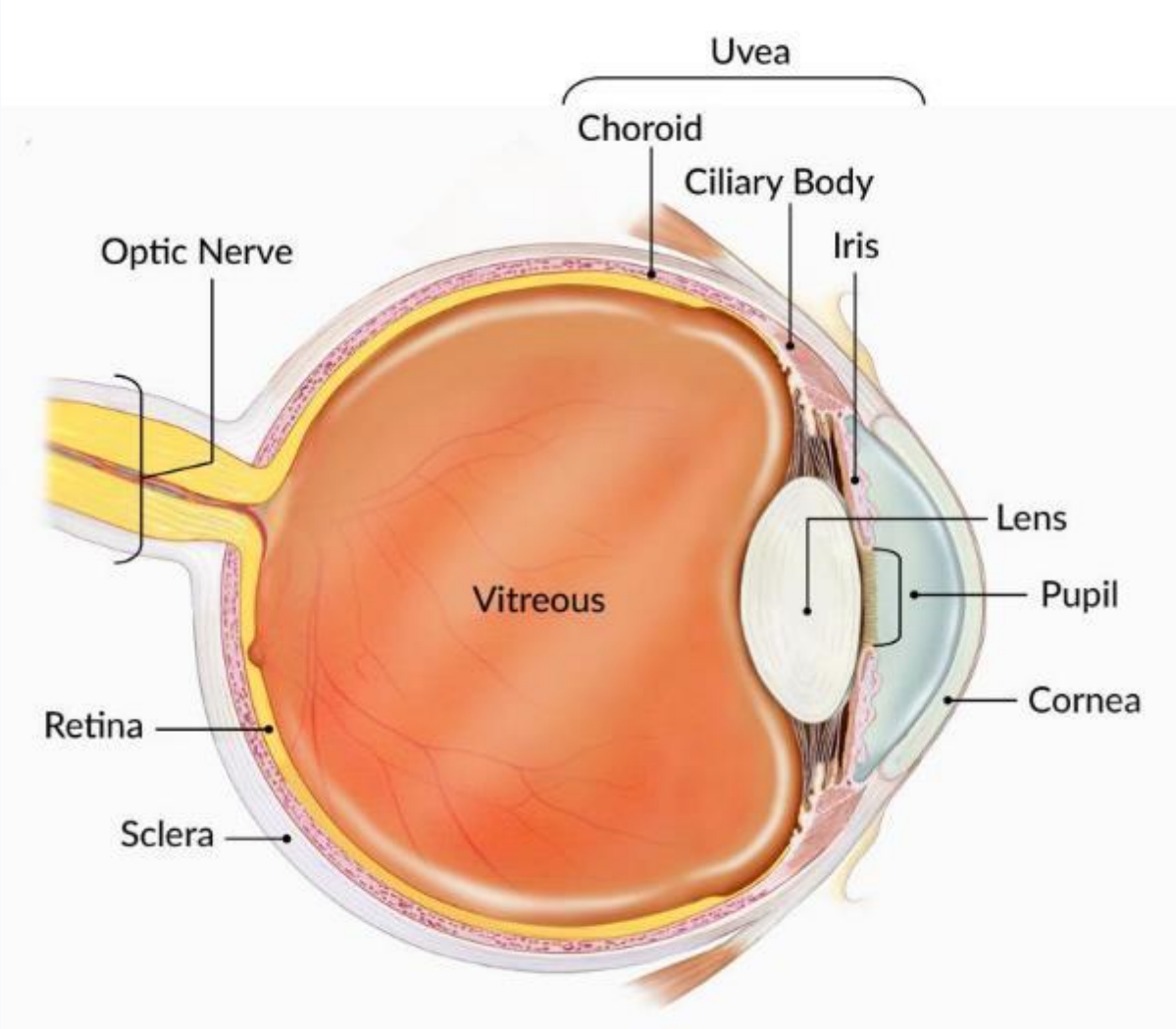




UV • linear polarization • circular polarization

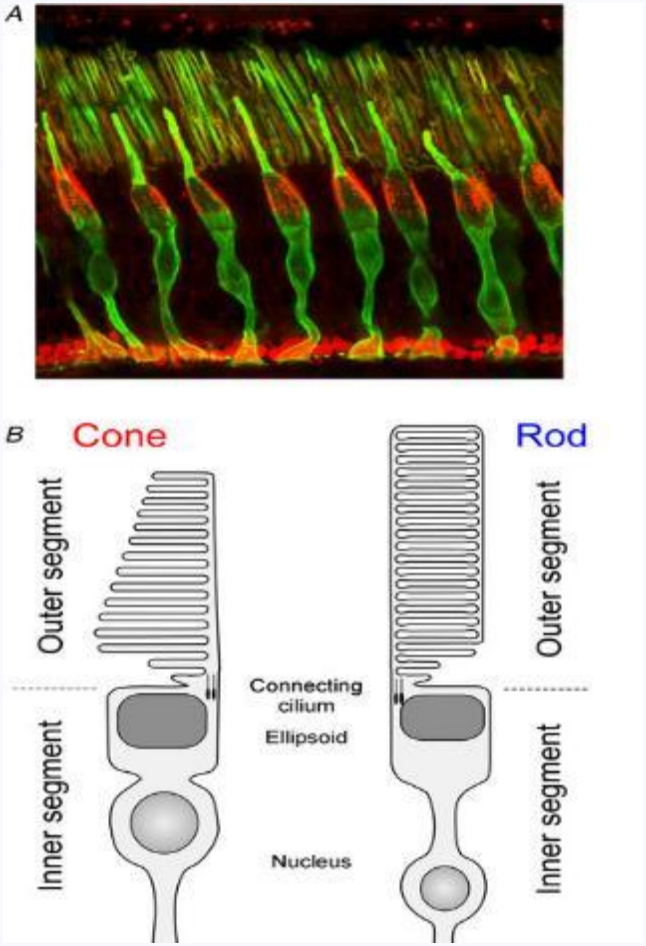
Cronin TW et al. Phil Trans R Soc B. 2014; Cronin TW, Bok MJ. J Exp Biol. 2016.

Optical Projection onto the Retina



Purves D et al. Neuroscience. 2nd ed. NCBI Bookshelf NBK11079.

Rod and Cone Photoreceptors



Feature	Cones	Rods
Outer segment	Open membrane sacs	Sealed discs
Sensitivity	Lower	Higher
Response	Faster	Slower
Operating range	Photopic vision	Scotopic vision

Rods maximize sensitivity; cones maximize speed and daylight vision

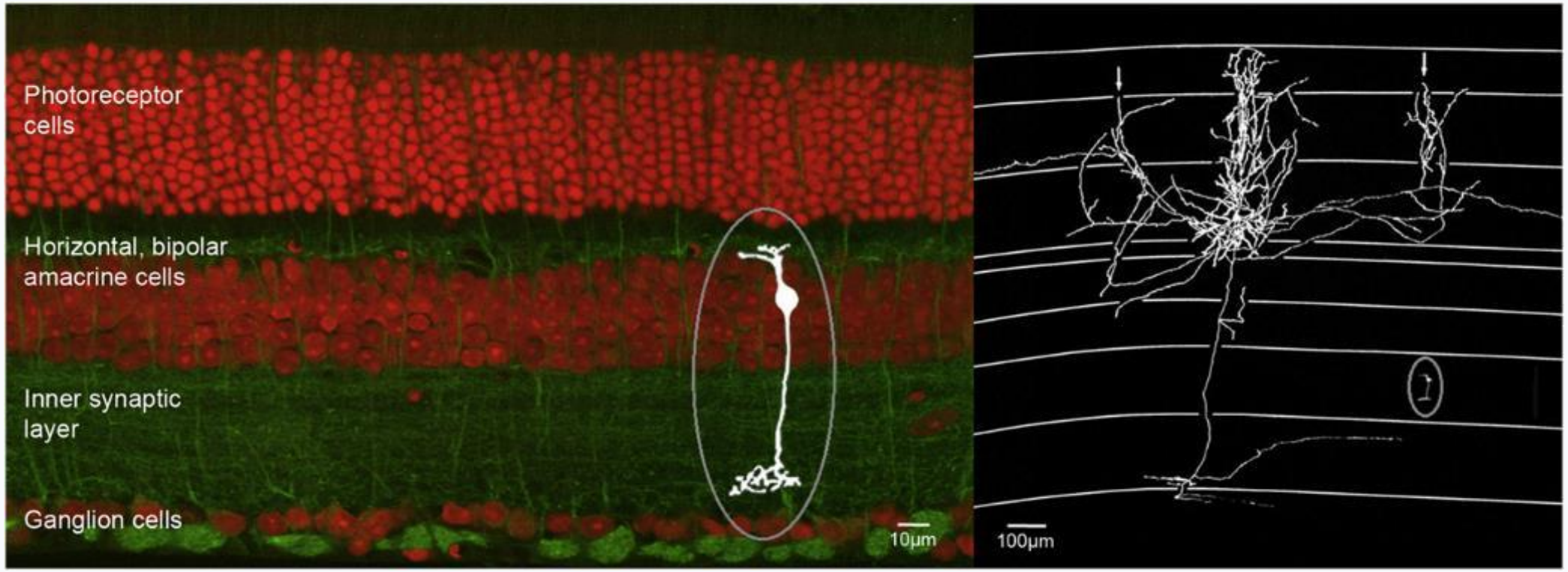
Lamb TD. J Physiol. 2022;600:4585–4601. Figure 1. doi:10.1113/JP282058

THREE QUESTIONS

01 What can be sensed?

02 What Does the Retina Compute?

Retinal Circuit Architecture

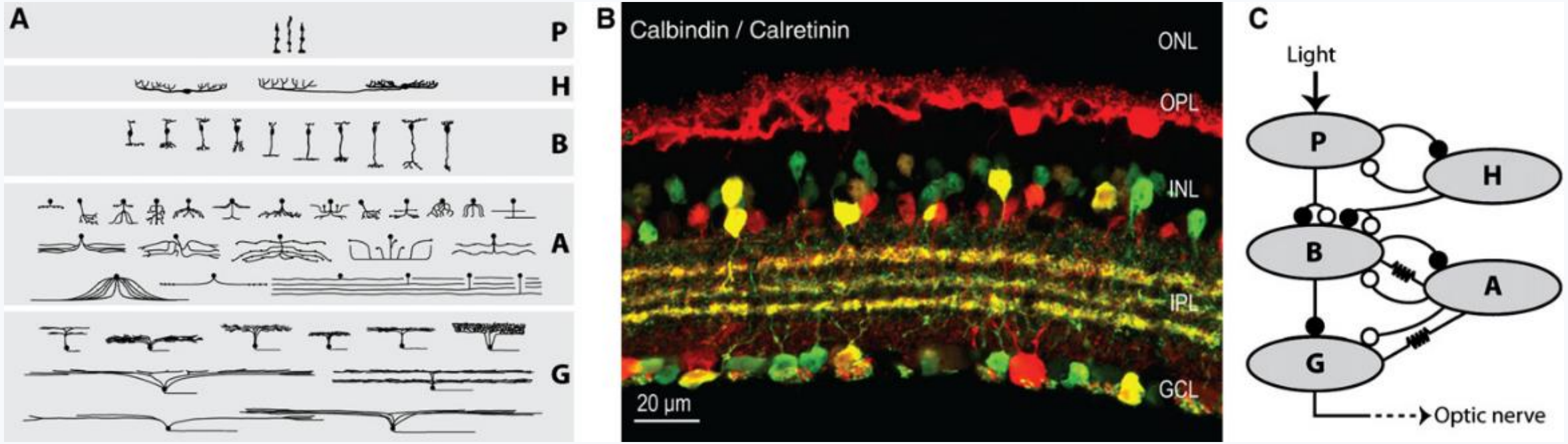


视网膜神经元尺度极小，光感受器、双极细胞、神经节细胞分层排列

视网膜是一整套微型神经回路，不是一张膜

Masland RH (2012) Neuron 76(1):266–280, Figure 1 (p.267)

Five Classes of Retinal Neurons



五类神经元如何互相连接，构成纵向通路与横向调制

光感受器、水平细胞、双极细胞、无长突细胞、神经节细胞；纵向传递之外还有大量横向连接

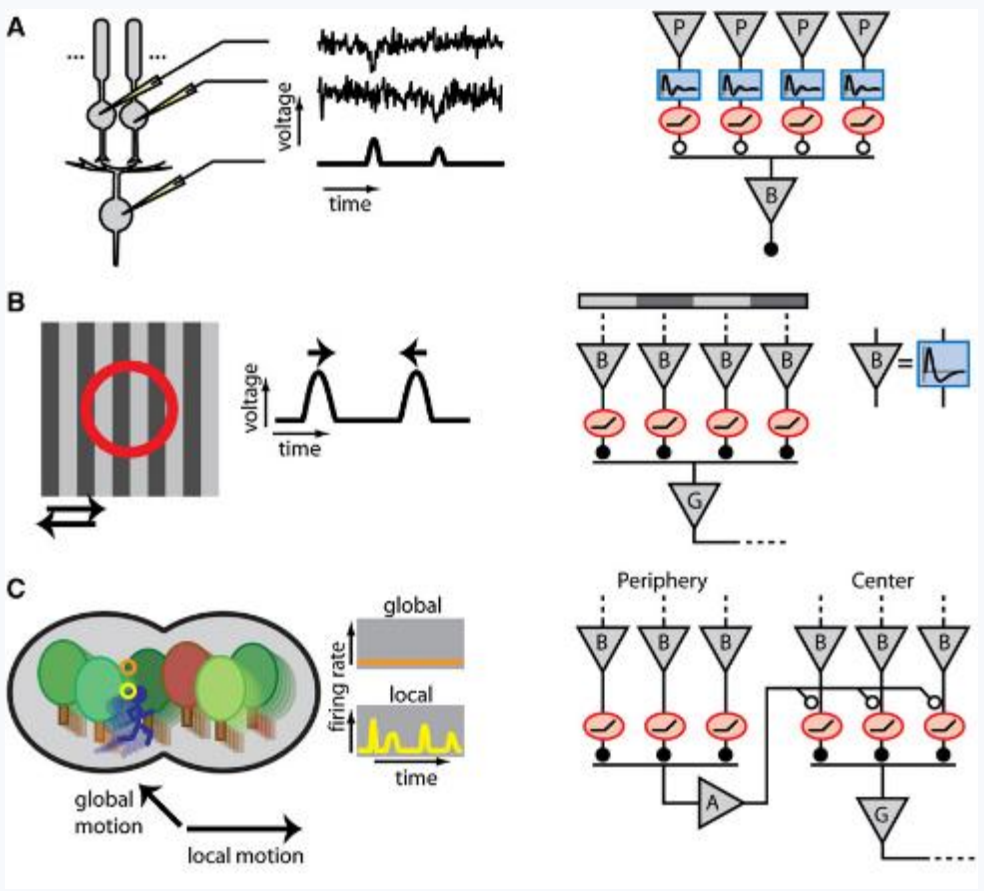
Gollisch T & Meister M (2010) Neuron 65(2):150–164, Figure 1 (p.151)

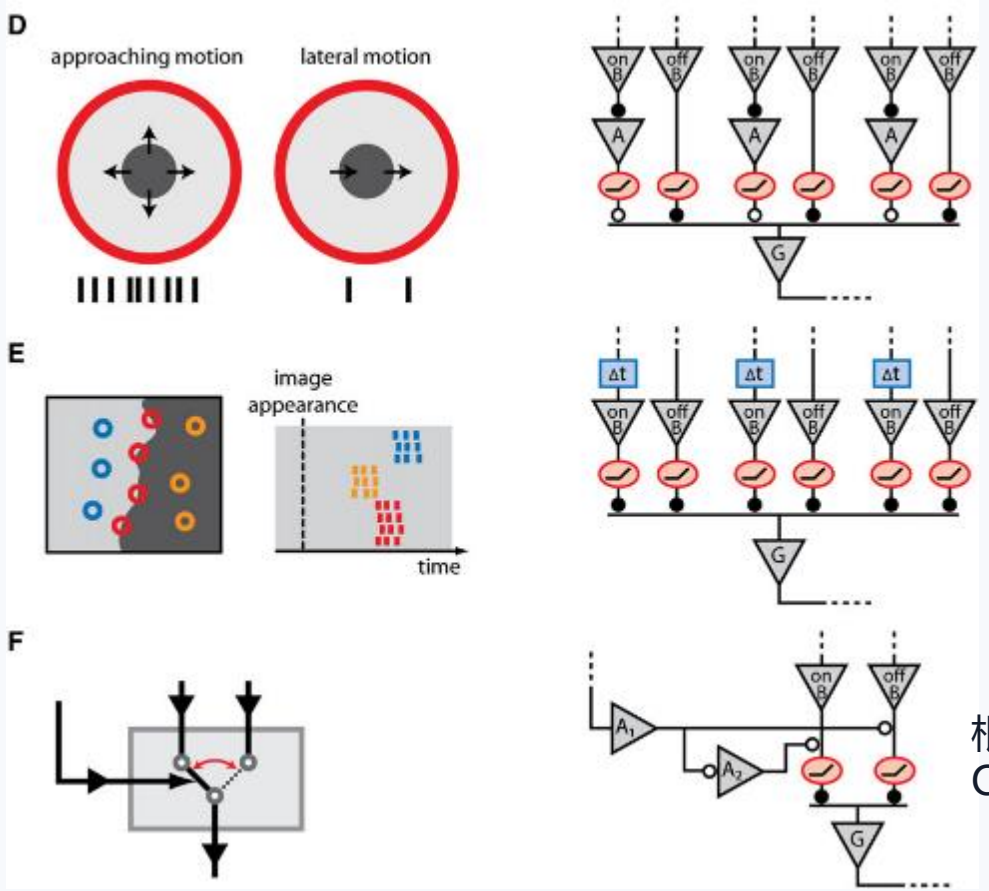
Computation in the Retina

噪声中检测单光子

检测纹理运动

区分整体运动与局部物体运动





检测接近的物体

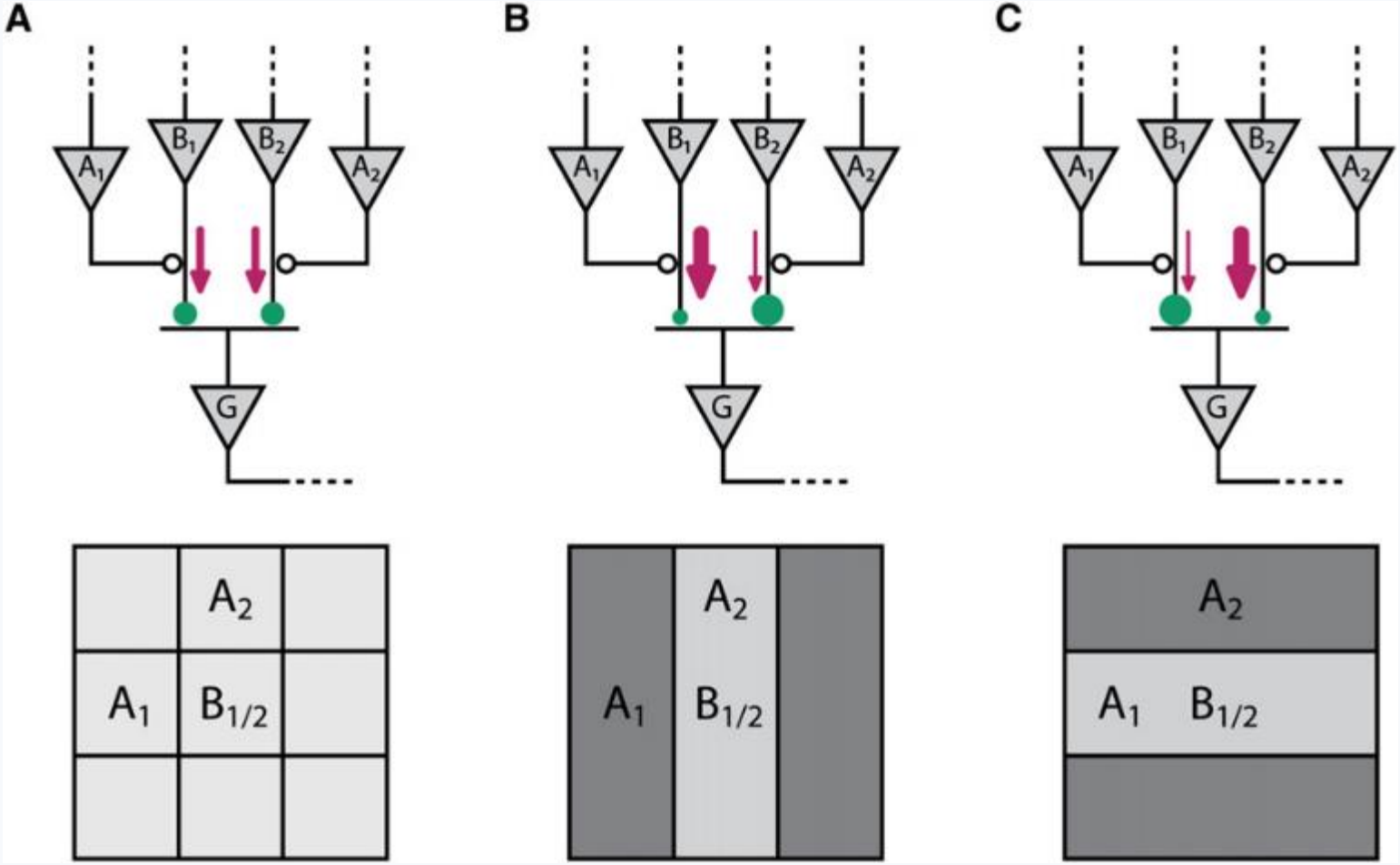
用放电时间编码空间结构

根据场景切换ON和OFF通路

Gollisch T & Meister M (2010) Neuron 65(2):150–164, Figure 2 (p.153)

Synaptic Computation

双极细胞终端的突触抑制带来图案适应与选择性

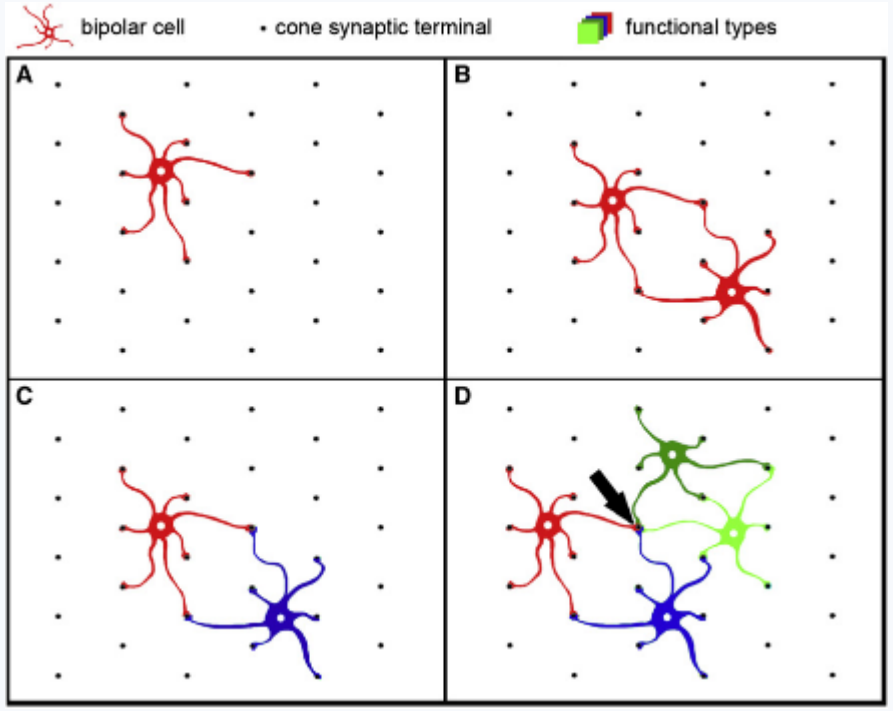


回路模型加上实测响应，显示重复刺激后反应衰减，新图案出现时恢复

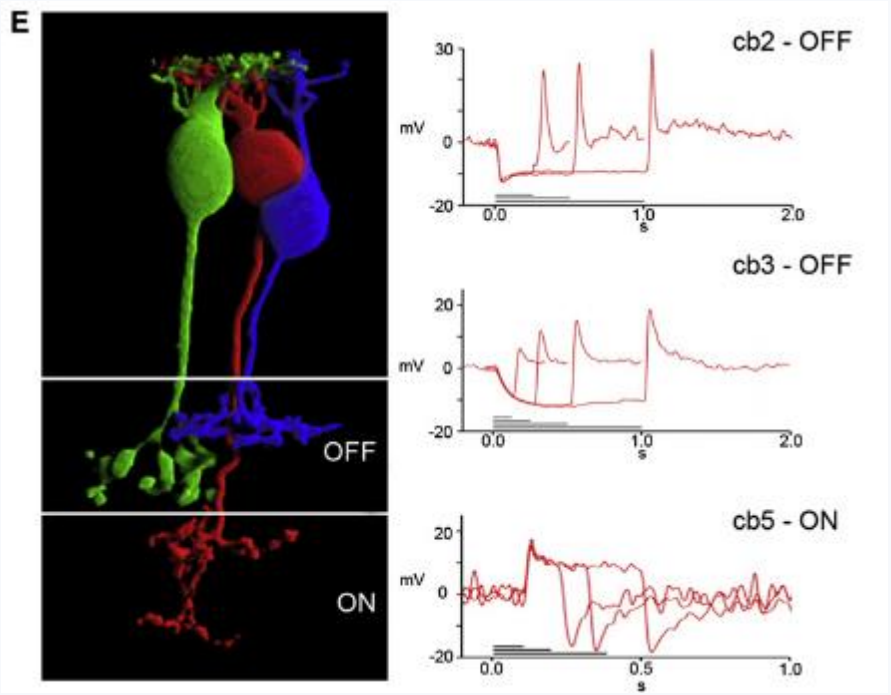
计算不需要复杂结构，突触本身就能实现

Gollisch T & Meister M (2010) Neuron 65(2):150–164, Figure 3 (p.157)

Parallel Pathways from a Single Cone



单个双极细胞接收感受野内所有视锥，同一视锥又分给多型双极细胞

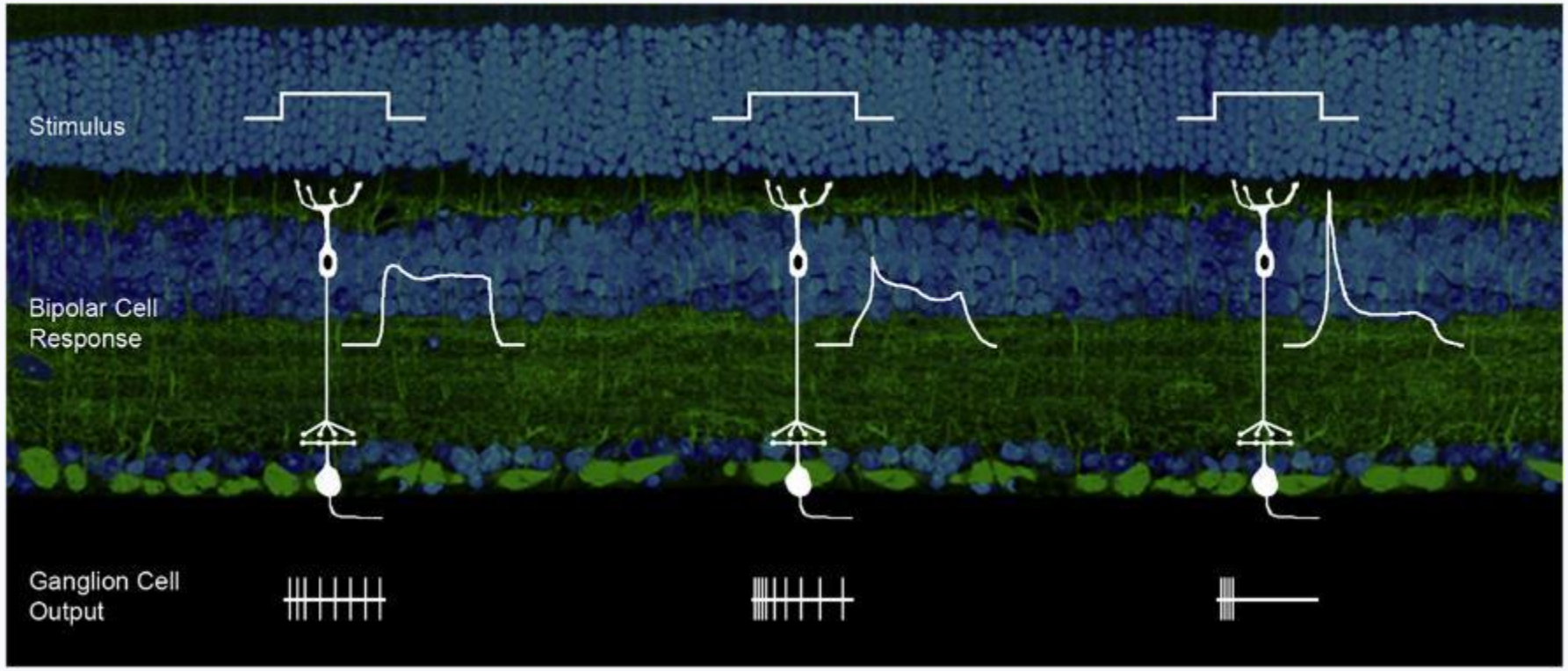


锥体输出发散进入由不同双极细胞介导的独立通道

并行不是冗余，而是同一信号的多种不同解析方式

Masland RH (2012) Neuron 76(1):266–280, Figure 3 (p.271)

Temporal Filtering in the Retina



不同时间特性的双极细胞，产生性质不同的神经节细胞

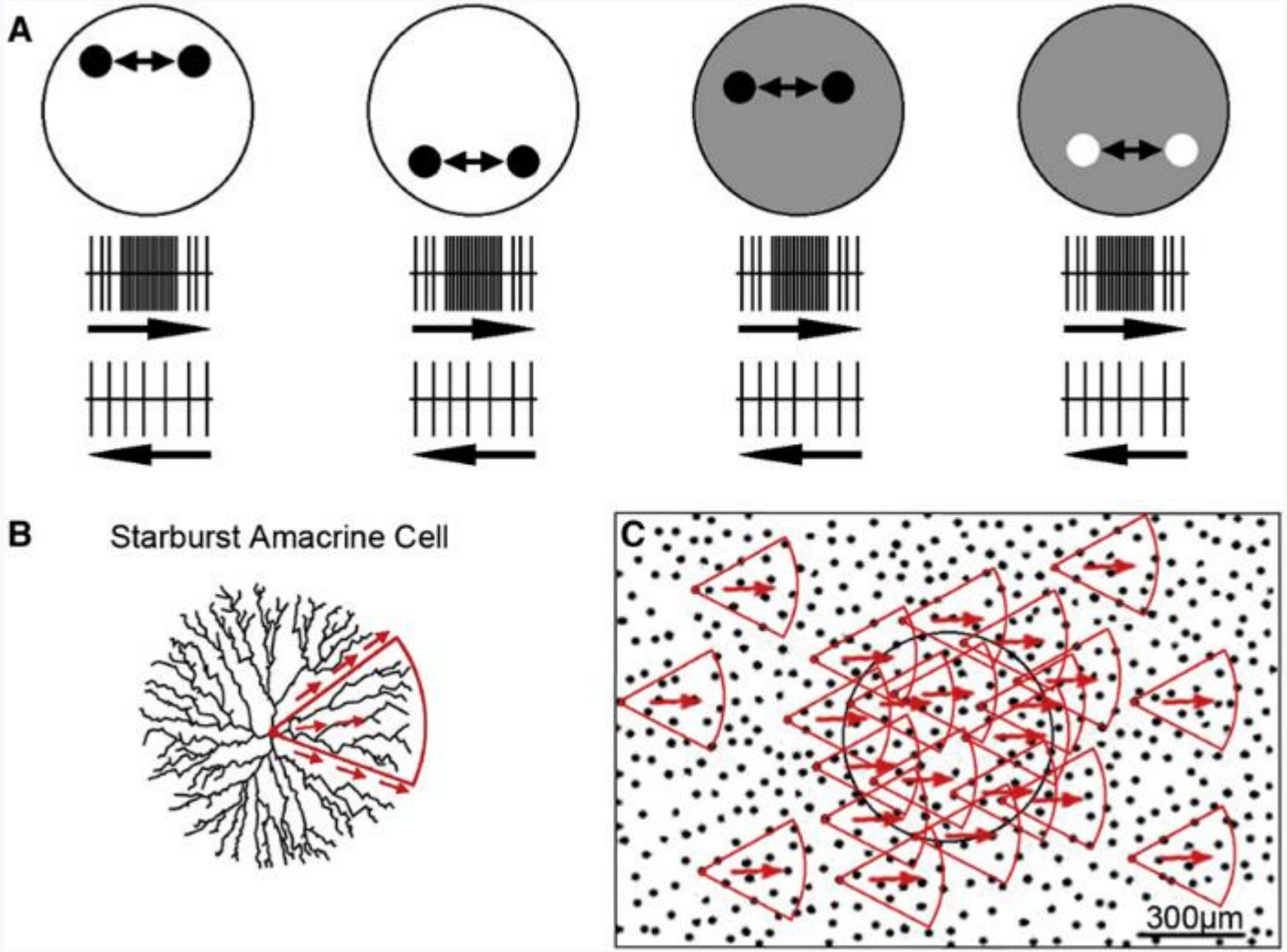
上游时间特性直接决定输出的时间模式

时间维度上的特征提取同样发生在视网膜内

Masland RH (2012) Neuron 76(1):266–280, Figure 4 (p.272)

Retinal Direction Selectivity

ON-OFF 方向选择性细胞可直接分辨运动方向，并给出其产生机制



细胞对特定方向运动强烈放电，对反方向几乎不反应

运动方向在视网膜就已被计算出来

Masland RH (2012) Neuron 76(1):266–280, Figure 7 (p.275)

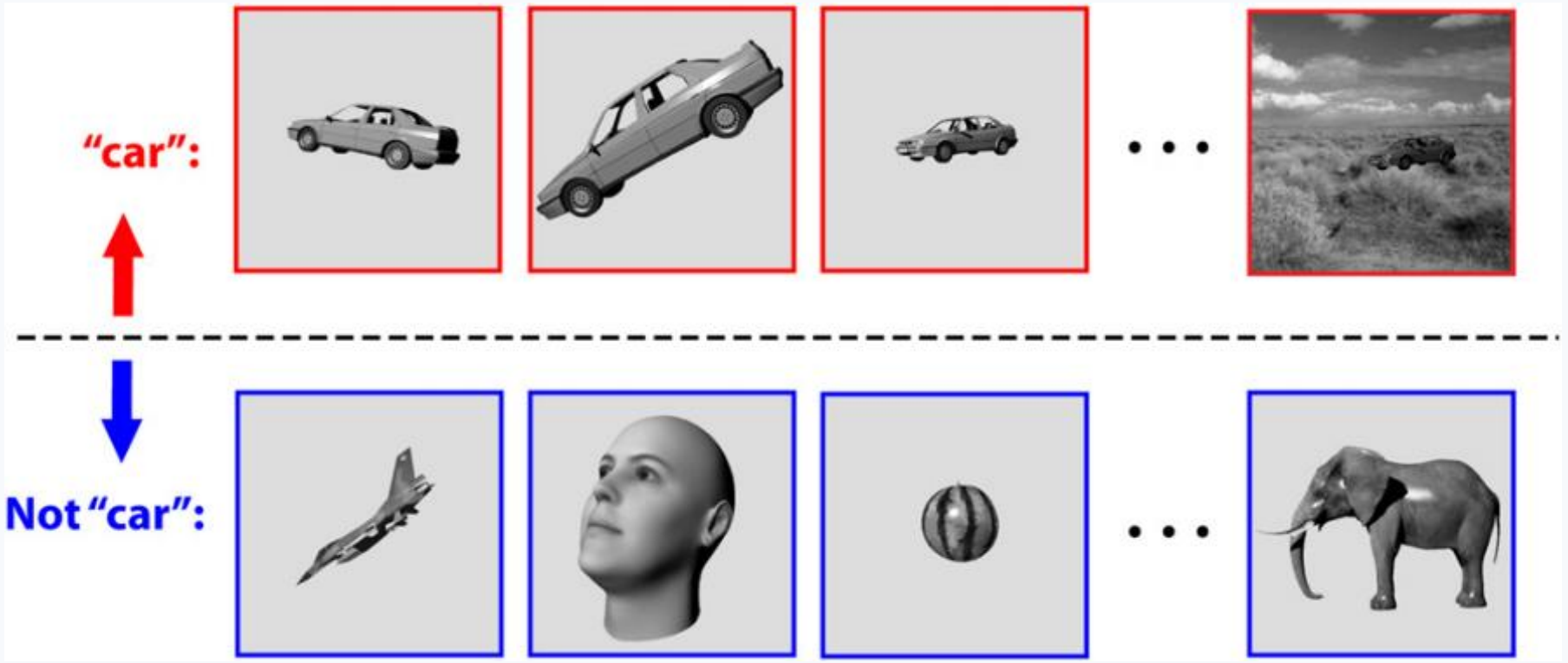
THREE QUESTIONS

01 What can be sensed?

02 What does the retina compute?

03 How Does Neural Activity Become Perception?

Invariant Object Recognition



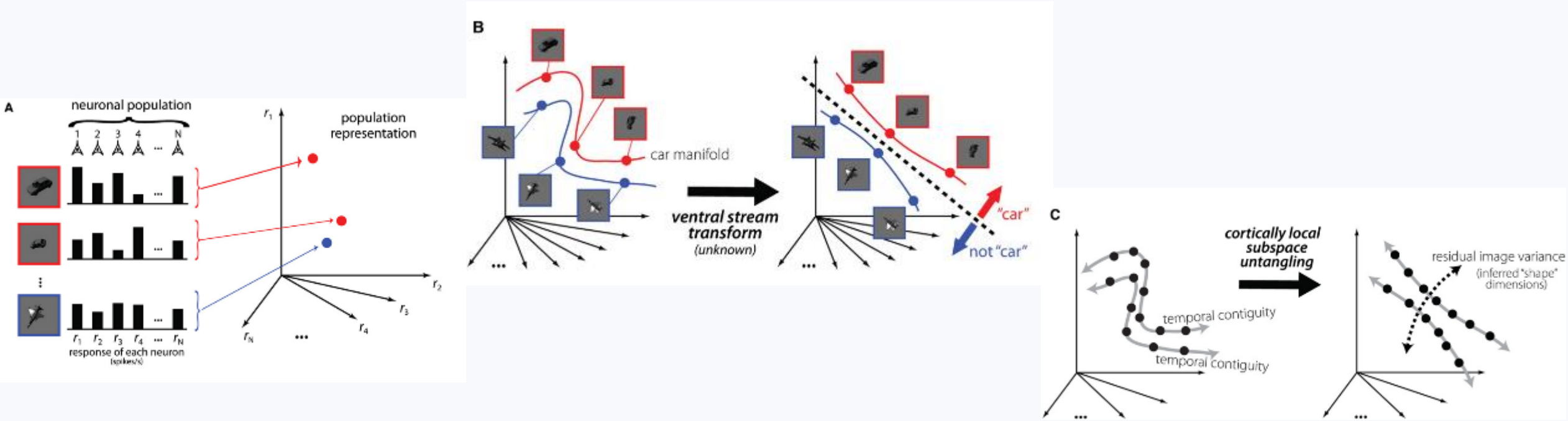
同一物体在不同视角、光照、大小、背景下，图像像素完全不同。

核心物体识别：在 200 毫秒内完成判别，且不受变换影响

识别的难点不是分类，而是不变性

DiCarlo JJ, Zoccolan D & Rust NC (2012) Neuron 73(3):415–434, Figure 1 (p.416)

Untangling Neural Representations



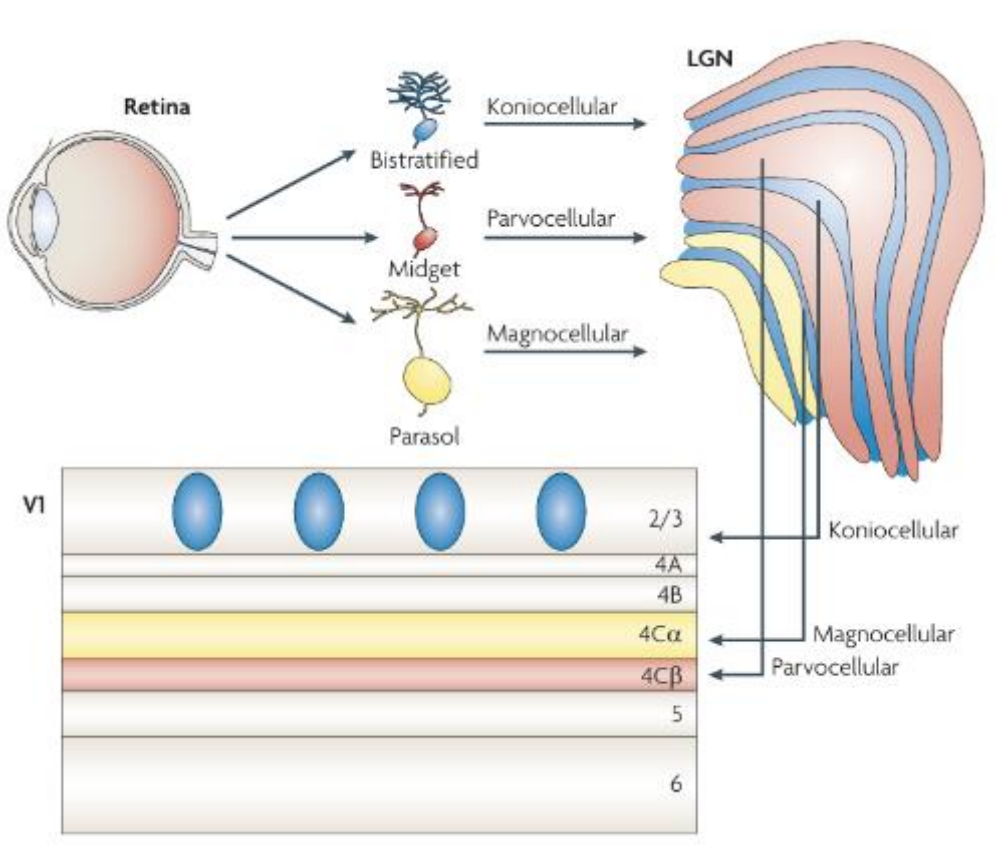
群体响应把每张图映射为高维空间中的一个点；同一物体形成流形

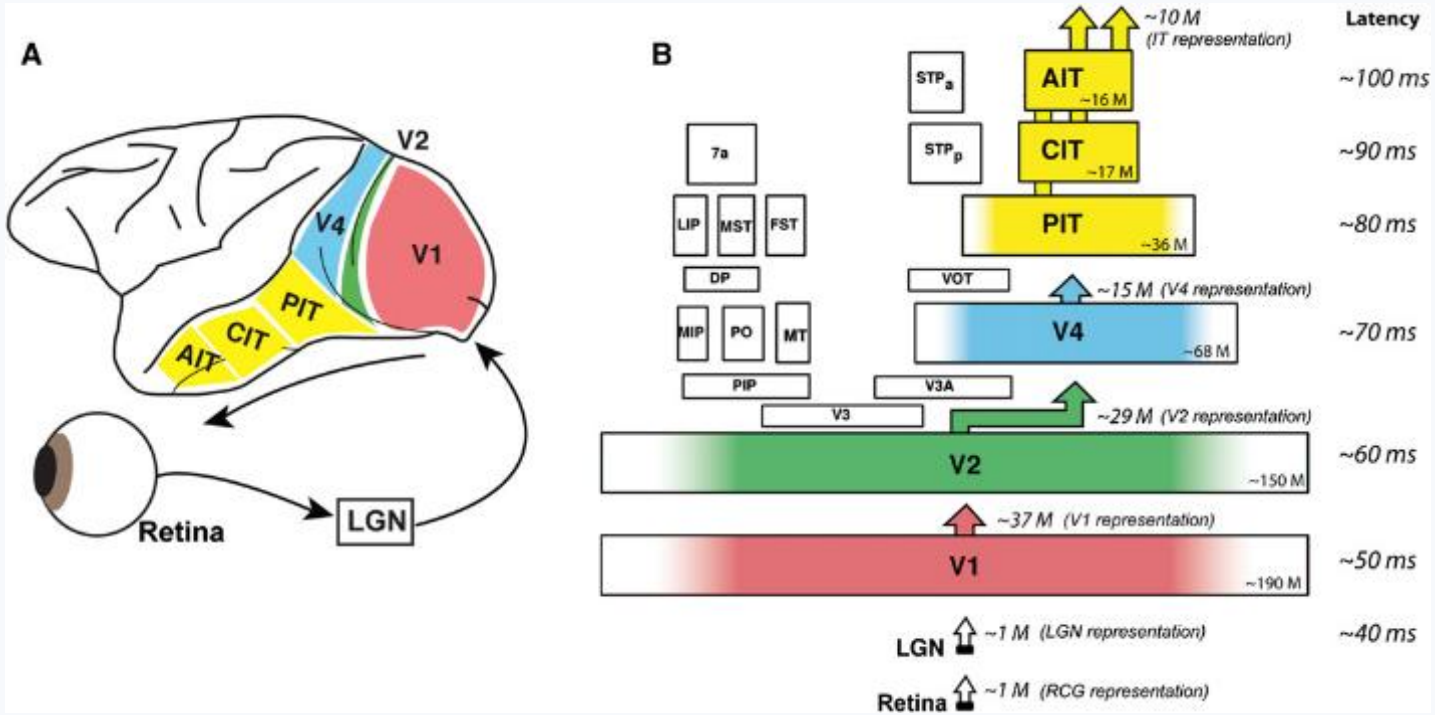
腹侧通路的变换把纠缠的流形拉开，使线性判别成为可能

识别 = 把表征变换到可以简单读出的形式

DiCarlo JJ et al. (2012) Neuron 73(3):415–434, Figure 2 (p.418)

The Ventral Visual Pathway





K:蓝-黄等相对独立的信息通道

P:看细节和颜色

M:看运动和快速变化

V1:局部边缘、线条、朝向、空间频率等

V2:轮廓、纹理、图形—背景关系等更复杂组合

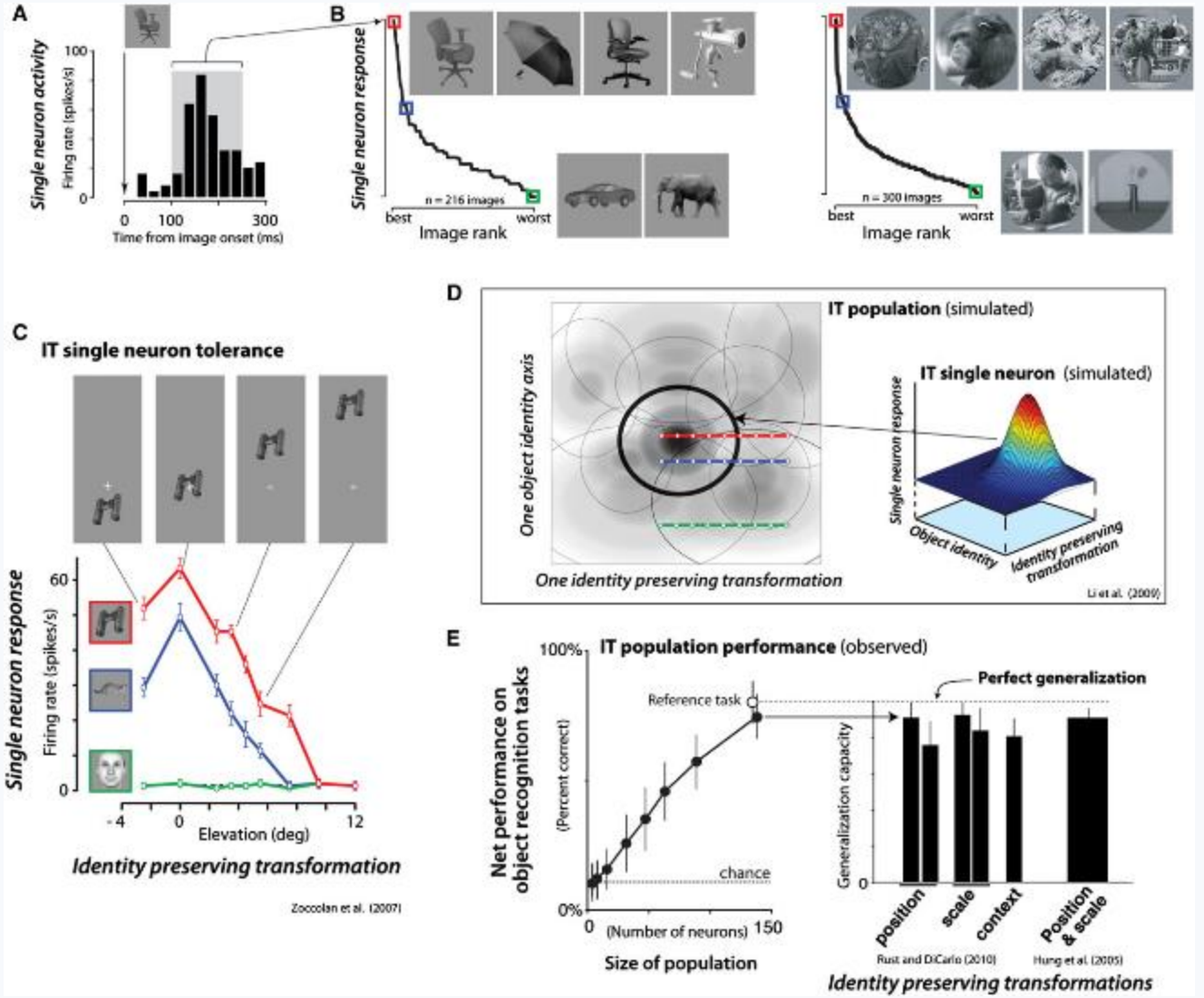
V4:颜色、曲率、较复杂形状和表面特征

IT:复杂物体表征、类别和物体识别

Nassi JJ et al. (2009) Nat Rev Neurosci

DiCarlo JJ et al. (2012) Neuron 73(3):415–434, Figure 3 (p.419)

Population Coding in IT Cortex

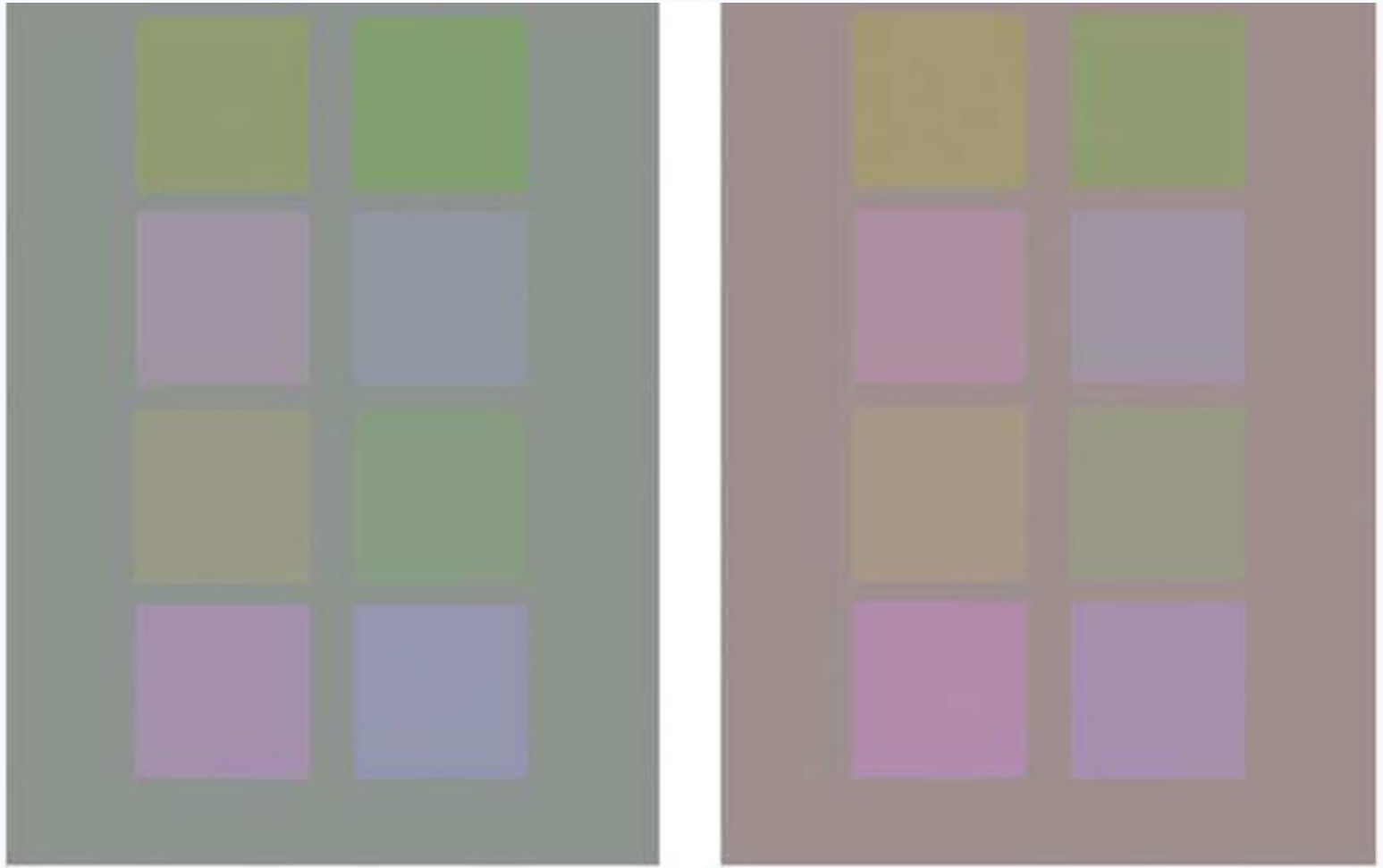


DiCarlo JJ et al. (2012) Neuron 73(3):415–434, Figure 4 (p.421)

视觉的基本单位是群体编码，不是单个概念细胞

Perception as Neural Construction

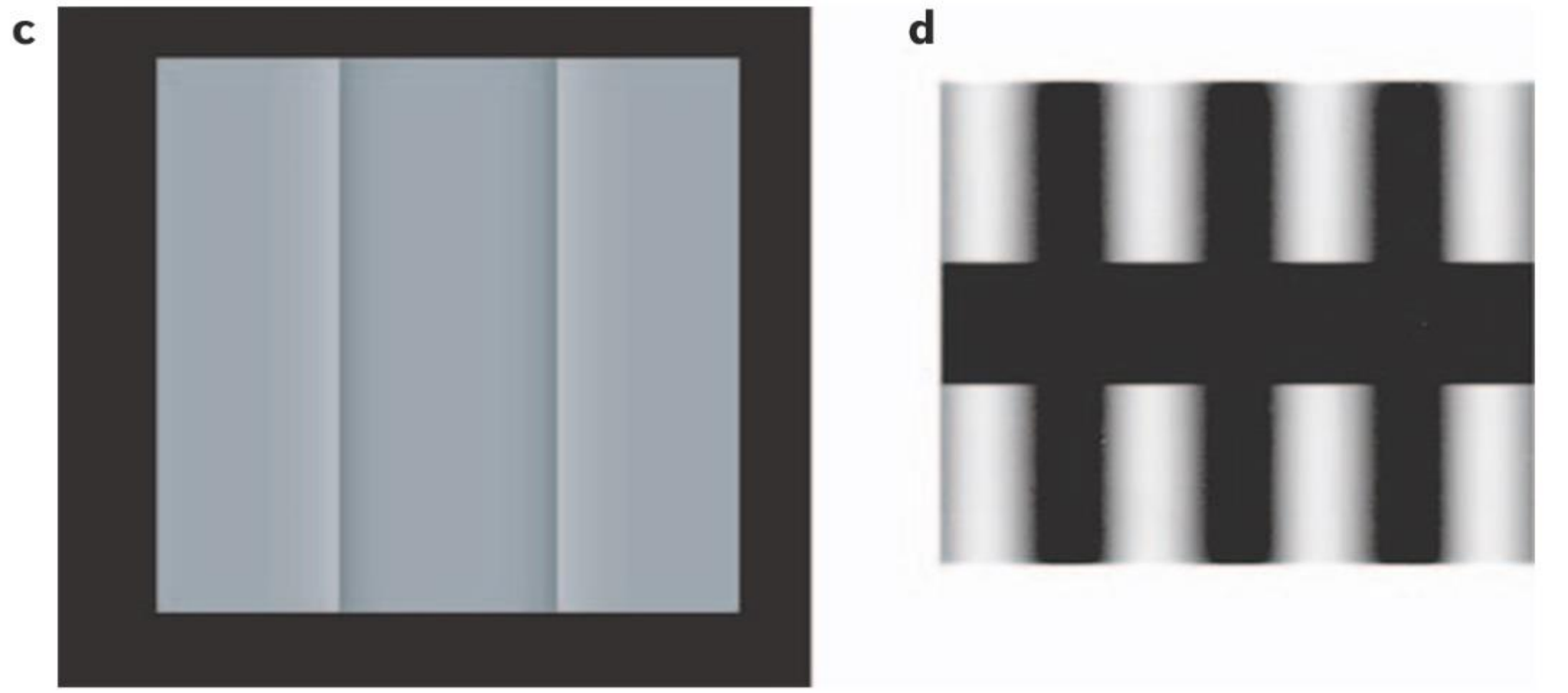
Color Constancy



颜色是大脑对光谱与环境共同推断的结果

Gegenfurtner KR (2003) Nat Rev Neurosci 4:563–572, Figure 3 (p.565)

Visual Filling-In

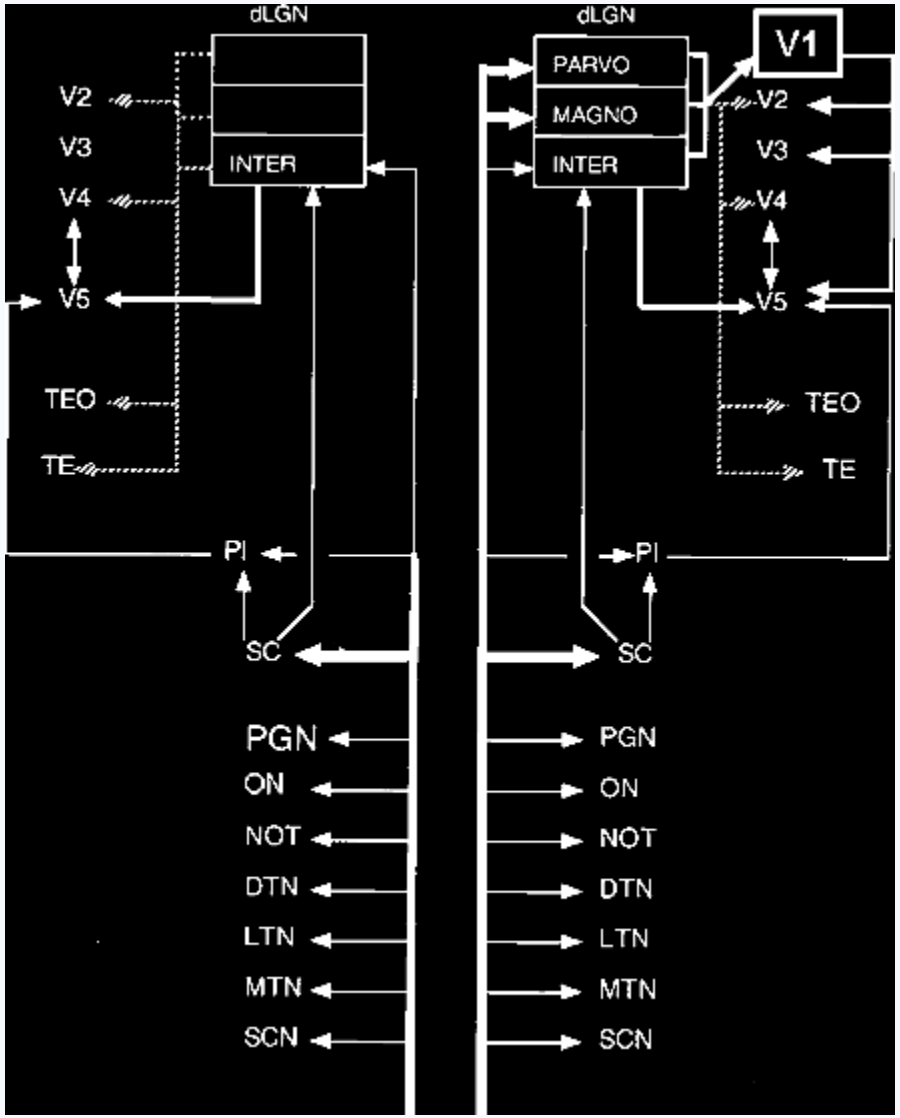


多种刺激都能诱发填补，包括盲点处的补全与人工盲区

注视中心时，落在盲点的目标消失，背景被自动延续

Komatsu H (2006) Nat Rev Neurosci 7:220–228, Figure 1 (p.221)

Visual Pathways Beyond V1



除经 LGN 到 V1 的主通路外，还有经上丘等结构的旁路

Cowey A (2010) Exp Brain Res 200:3–24 (p.11)

PART I CONCLUSION

Vision as Computation

1. Light → Sensation → Neural encoding → Circuit computation → Population representation → Perception
2. The retina performs computations; the world is decomposed into dozens of parallel channels
3. The cortex progressively decodes object identities; what we subjectively see is constructed by the brain.

References

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2 Simons DJ, Rensink RA. Trends Cogn Sci. 2005. 10.1016/j.tics.2004.11.006

3 Cronin TW, Bok MJ. J Exp Biol. 2016. 10.1242/jeb.128769

4 Cronin TW et al. Phil Trans R Soc B. 2014. 10.1098/rstb.2013.0032

5 Gracheva EO et al. Nature. 2010. 10.1038/nature08943

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8 Gollisch T, Meister M. Neuron. 2010. 10.1016/j.neuron.2009.12.009

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10 Hubel DH, Wiesel TN. J Physiol. 1962. 10.1113/jphysiol.1962.sp006837

11 DiCarlo JJ et al. Neuron. 2012. 10.1016/j.neuron.2012.01.010

12 Leopold DA. Annu Rev Neurosci. 2012. 10.1146/annurev-neuro-062111-150356

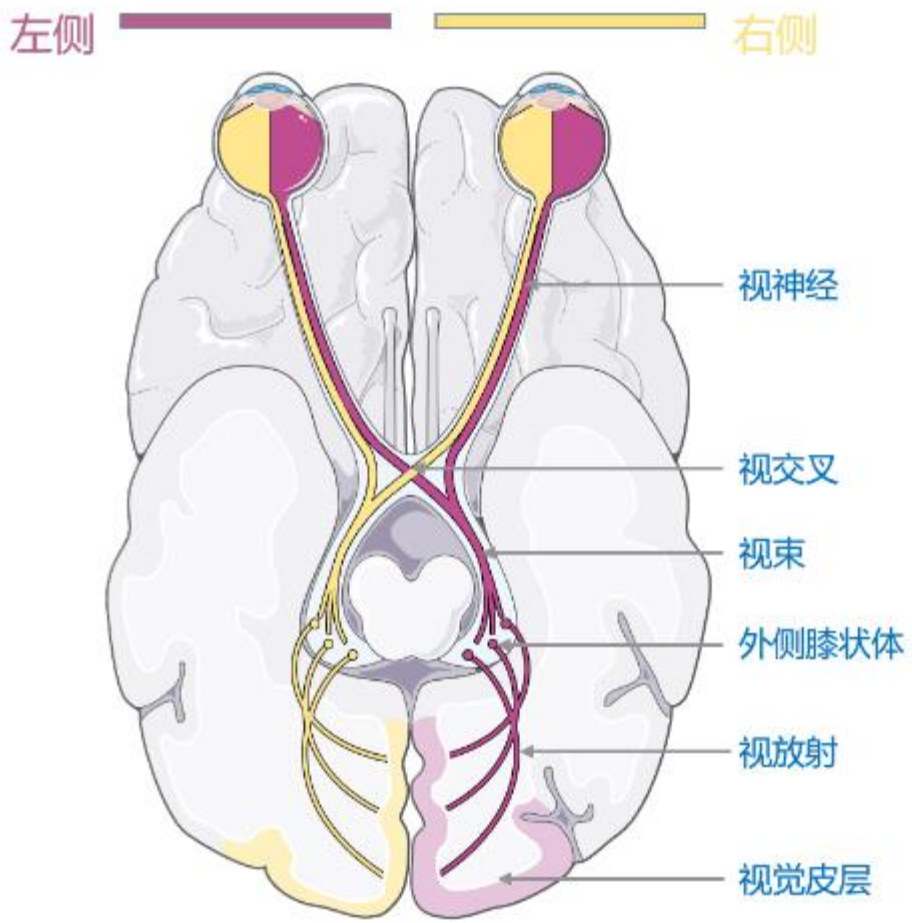
PartII： When Vision Fails: Can We Restore Sight?

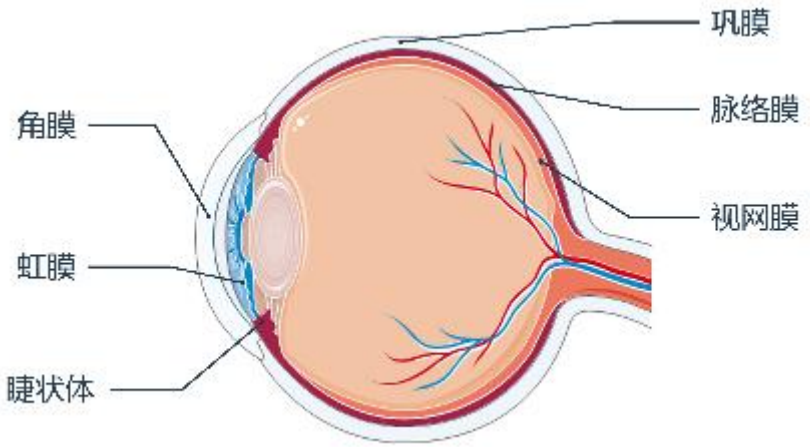
WYJ
2026.9.24

- Where does vision go wrong?
- When photoreceptors fail, can we provide visual input to the brain in new ways?
- Can we bypass the eyes and stimulate the brain to create vision?

When Vision Fails: Can We See Again?

visual pathway　　Eye → Retina → Optic Nerve → Brain





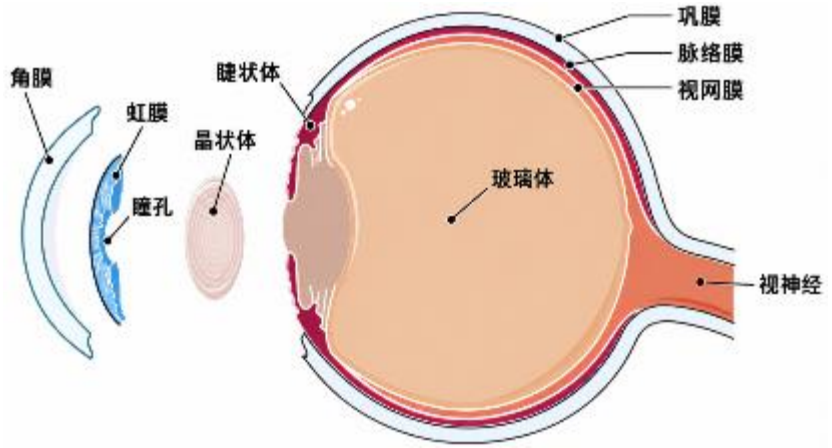
1.光学系统（Optics）：角膜、房水、瞳孔、晶状体、玻璃体等

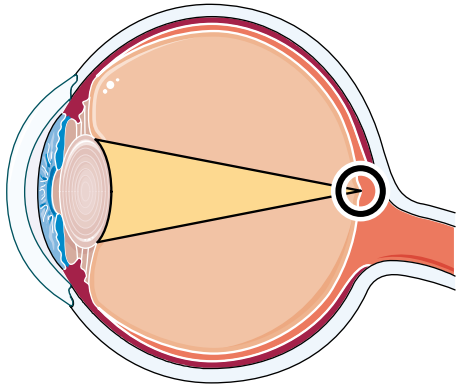
2.视网膜（Retina）：感光细胞、双极细胞、水平细胞、无长突细胞、神经节细胞等

3.视神经（Optic nerve）：RGC 轴突、视神经、视交叉、视束，进一步到 LGN 等

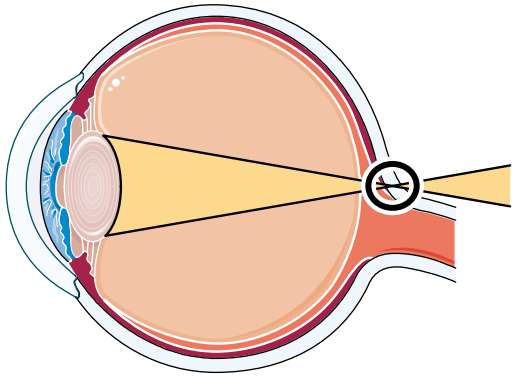
4.视觉皮层（Visual cortex）：V1、V2、V3、V4、MT/V5 等视觉皮层区域

The first way vision can fail: light focuses in the wrong place.

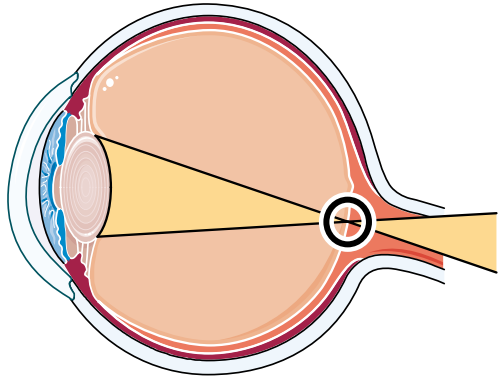




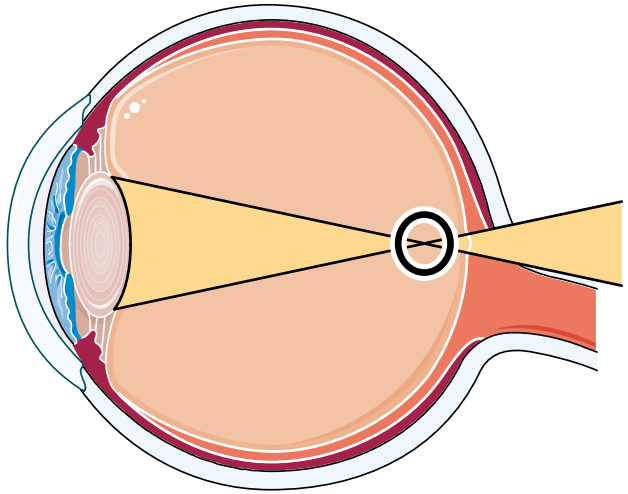
正常眼



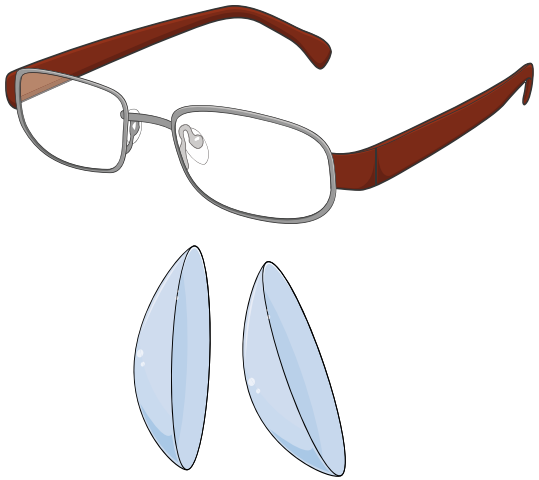
远视眼

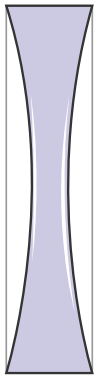


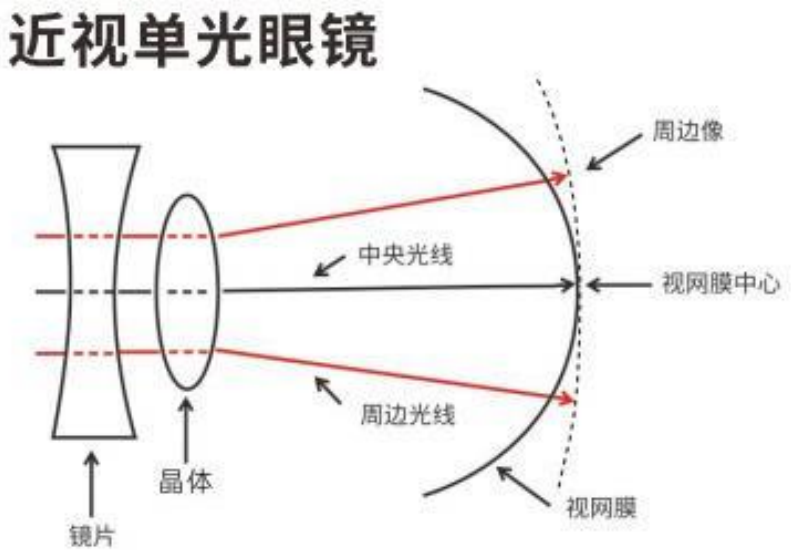
散光眼



近视眼







Is all vision loss the same?

Normal



青光眼



白内障



糖尿病视网膜病变

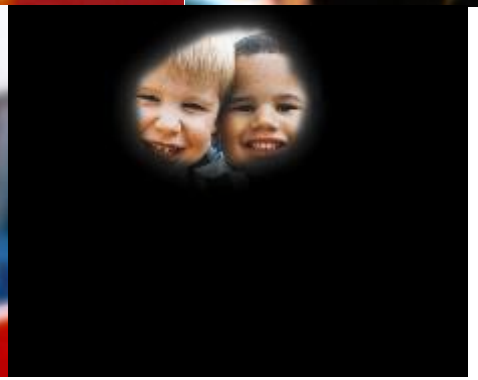




年龄相关性黄斑变性 (AMD)



近视

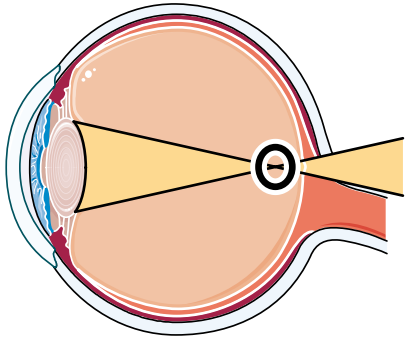


色素性视网膜炎

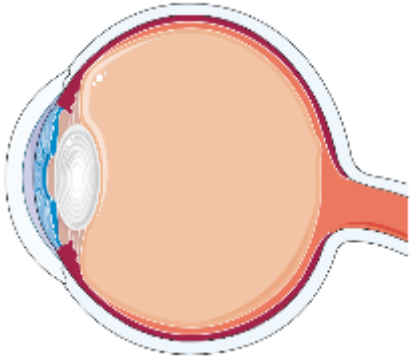
糖尿病视网膜病变，色素性视网膜炎，青光眼，年龄相关性黄斑变性，白内障，近视

Closing your eyes ≠ what a blind person sees

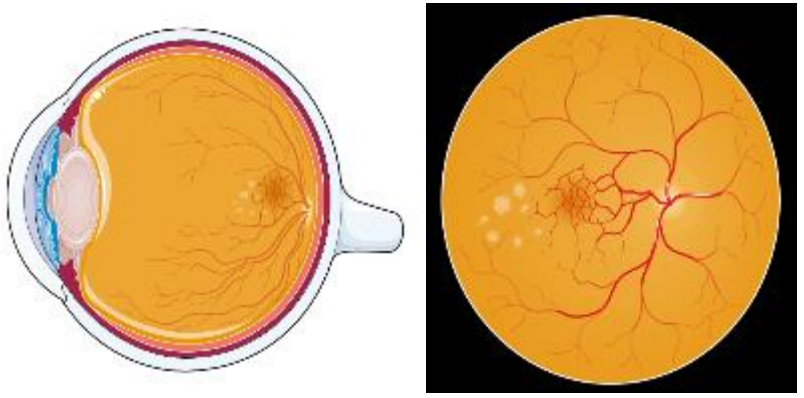
One Symptom, Different Failures



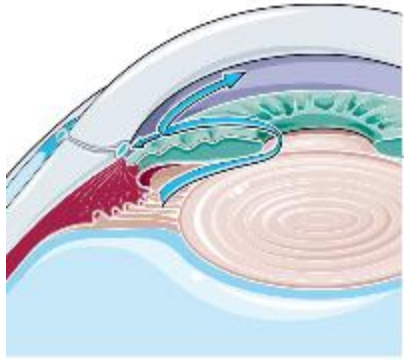
近视眼



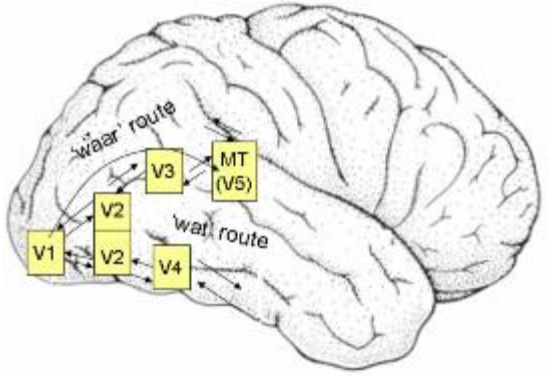
白内障



黄斑变性



青光眼



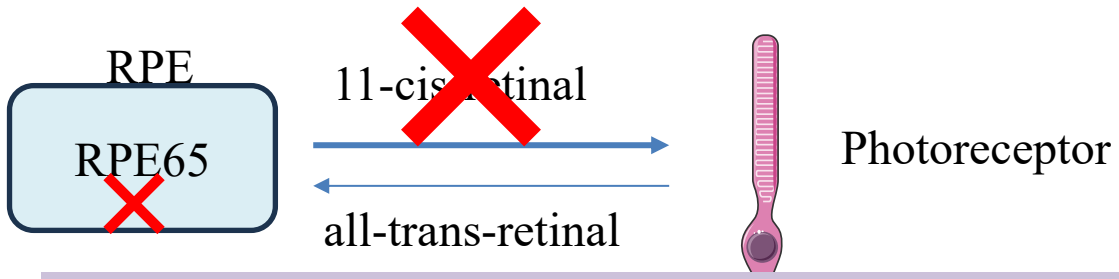
皮层盲

近视	光学几何结构
白内障	晶状体
年龄相关性黄斑变性	黄斑 / 视网膜色素上皮（RPE）/ 感光细胞
青光眼	视网膜神经节细胞 / 视神经
皮层盲	视觉皮层

- Where does vision go wrong?
- When photoreceptors fail, can we provide visual input to the brain in new ways?
- Can we bypass the eyes and stimulate the brain to create vision?

What If the Cells Are Still Alive, but the Program Is Broken?

RPE65-mediated inherited retinal dystrophy



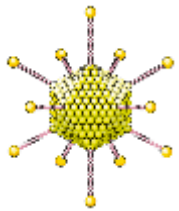
Gene therapy works only if there are cells left to rescue.
But What If the Photoreceptors Are Already Gone?

↓ **Photoreceptor remains light-sensitive**

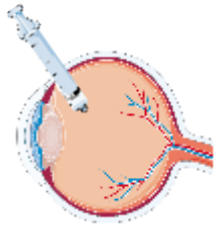
↓ Severe low-light visual dysfunction



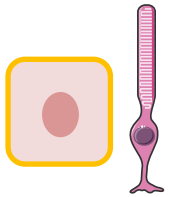
Gene replacement therapy



AAV2 functional RPE65 cDNA

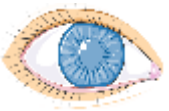


Subretinal injection

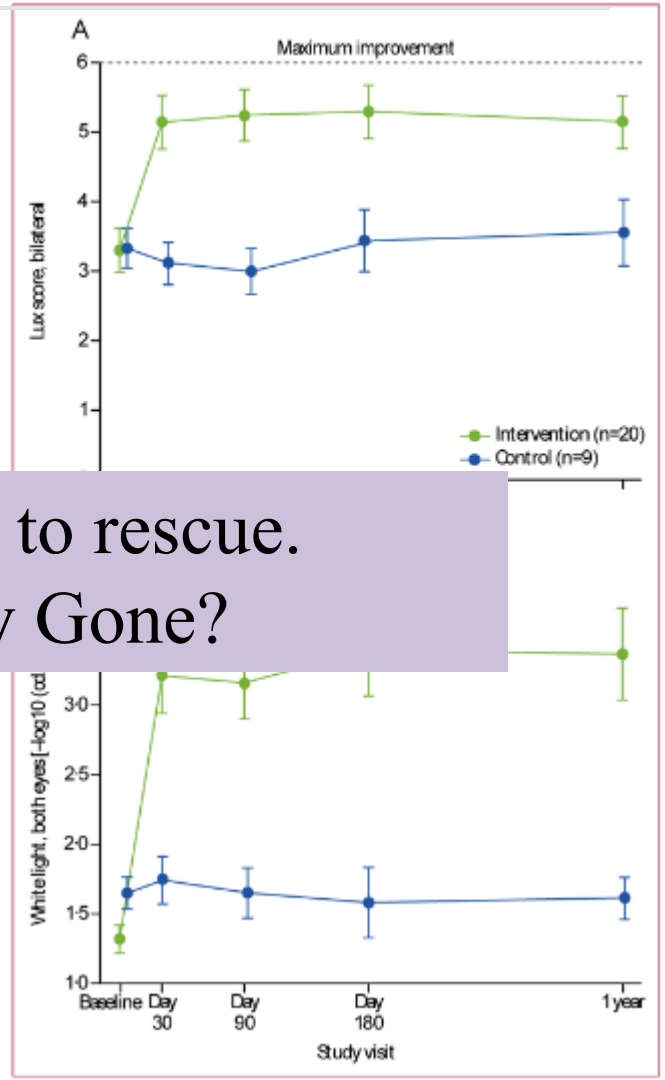


RPE/RPE-associated target cells

RPE65 function restored



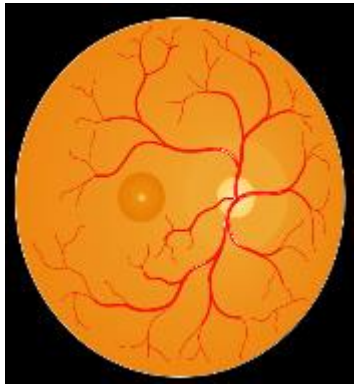
Improved functional vision



Russell S, et al. Lancet. 2017 Aug 26;390(10097):849-860.

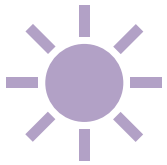
If photoreceptors are gone, can we bypass them?

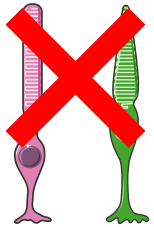
Normal retina



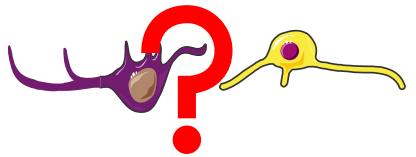
Photoreceptors capture lights and initiate visual signaling

Light → Photoreceptor 感光细胞 → Bipolar cell 双极细胞 → Ganglion cell 神经节细胞 → Optic nerve 视神经











Degenerated or lost, but some downstream neural circuits may still be partially preserved

Gene replacement therapy → **Needs surviving target cells**

Can We Make a Blind Retina Light-Sensitive Again?

Optogenetic vision restoration

Degenerated retina

No photoreceptors , no normal light input

Light

Photoreceptor
感光细胞



Bipolar cell
双极细胞



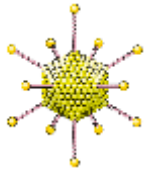
Ganglion cell
神经节细胞



Optic nerve
视神经

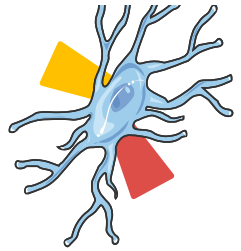


Optogenetic engineering



AAV vector

ChrimsonR

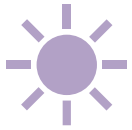


Retinal ganglion cells

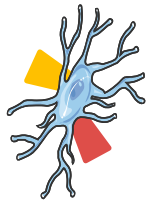
Engineered retina

Bypass the missing photoreceptors

Light



ChrimsonR+RGC



Optic nerve



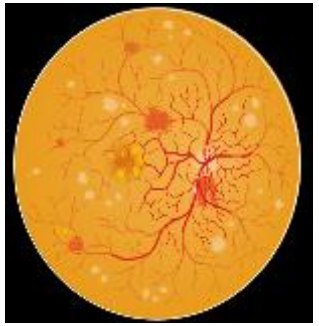
Brain



A Blind Patient Saw Objects Again——How did they restore visual input?



Retinitis pigmentosa
Long-standing blindness
Photoreceptor degeneration



Treatment components

1.AAV-2.7m8-CAG-ChrimsonR-tdTomato玻璃体腔注射

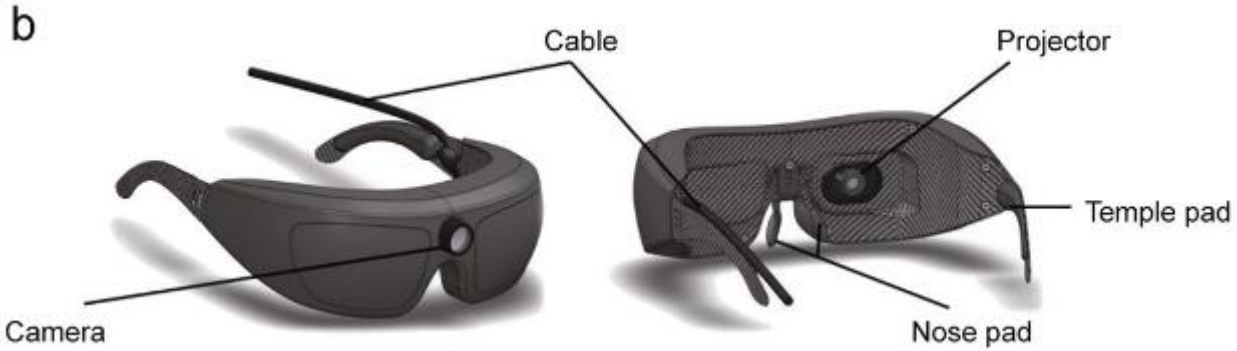
2.配合595nm light-stimulating goggles 使用

From light in the world to perception in the brain

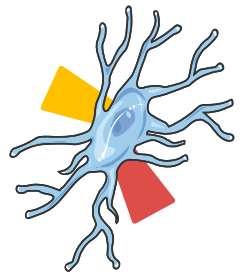
Scene → Camera → Processing → 595 nm light → ChrimsonR+ RGCs



Visual scene



goggles

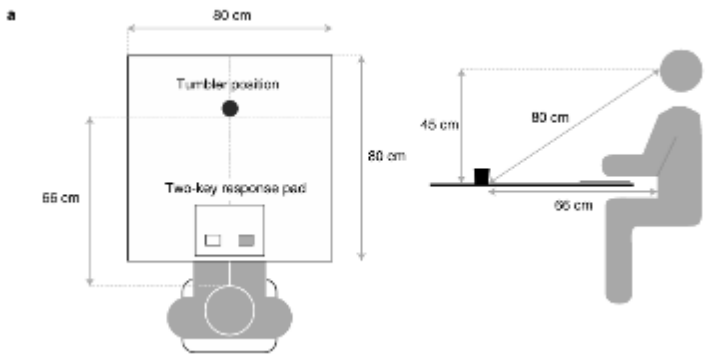


Retinal ganglion cells

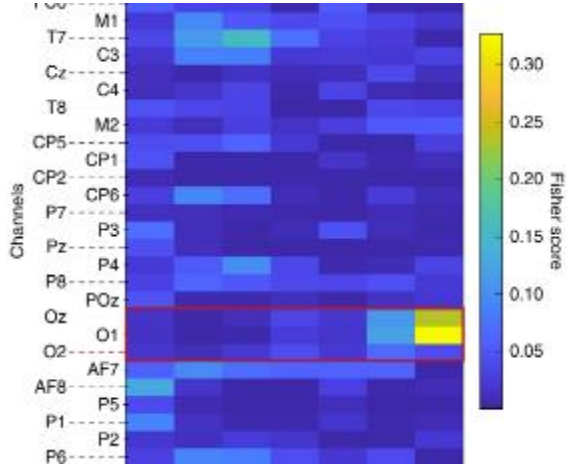
ChrimsonR+RGC

Sahel JA, et al. Nat Med. 2021 Jul;27(7):1223-1229.

A Blind Patient Saw Objects Again——Did the patient actually see?







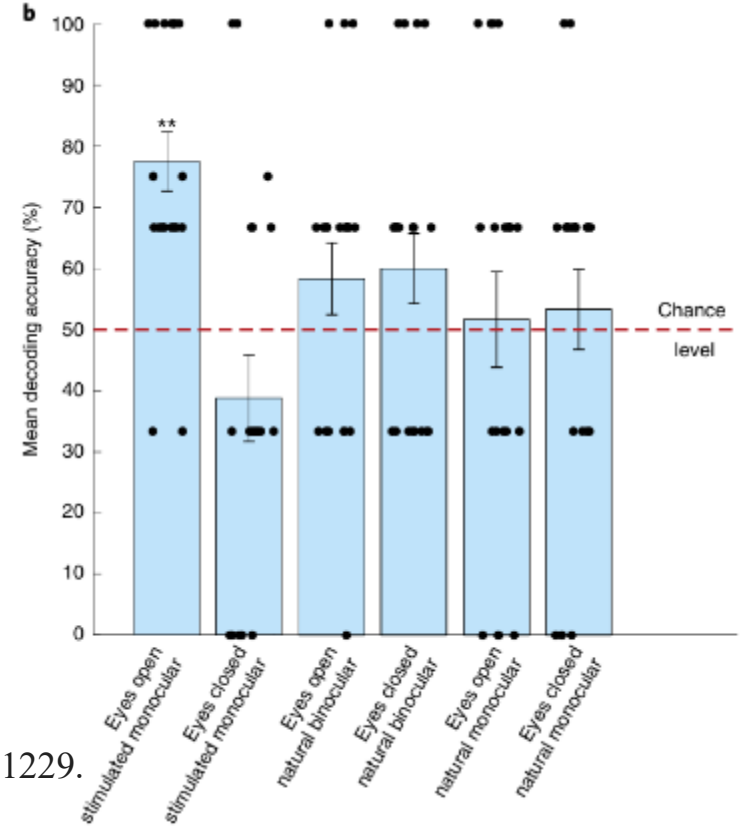
What could he do?

Perceive

Locate

Count

Touch



大物体任务：**36/39 trials 成功**

EEG object/no-object decoding：**约78%**

双眼自然观看	×
治疗后、不戴 goggles	×
治疗后 + goggles	√

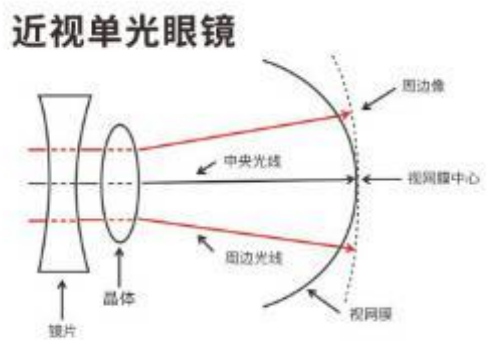
Partial functional vision ≠ normal vision

Sahel JA, et al. Nat Med. 2021 Jul;27(7):1223-1229.

Maybe We Don't Need Photoreceptors at All

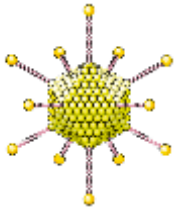
Optical correction

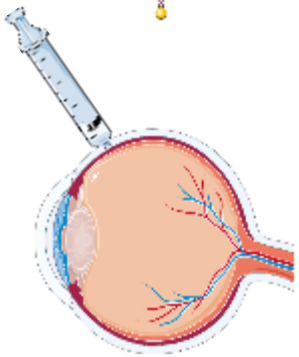




Correct the input
Retina and brain are intact
Photoreceptors needed

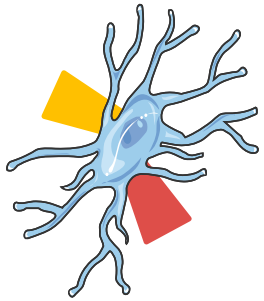
Biological repair





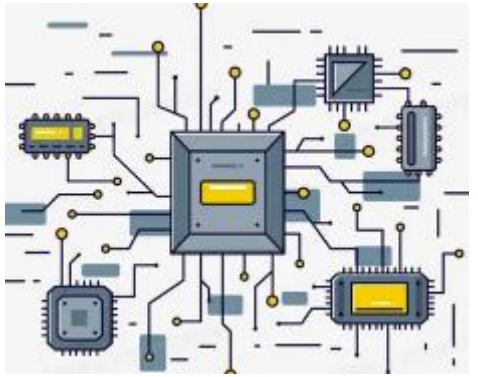
Gene therapy
Retina a molecular defect
Photoreceptors needed

Biological reprogramming



Repair → Bypass

Engineering replacement

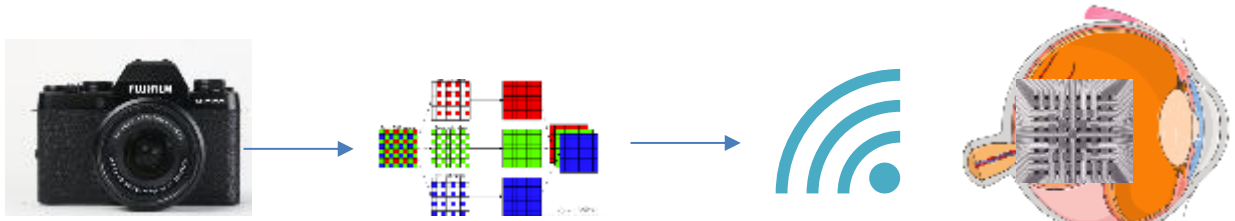


Optogenetics
Give surviving neurons a new function
Not Photoreceptors needed

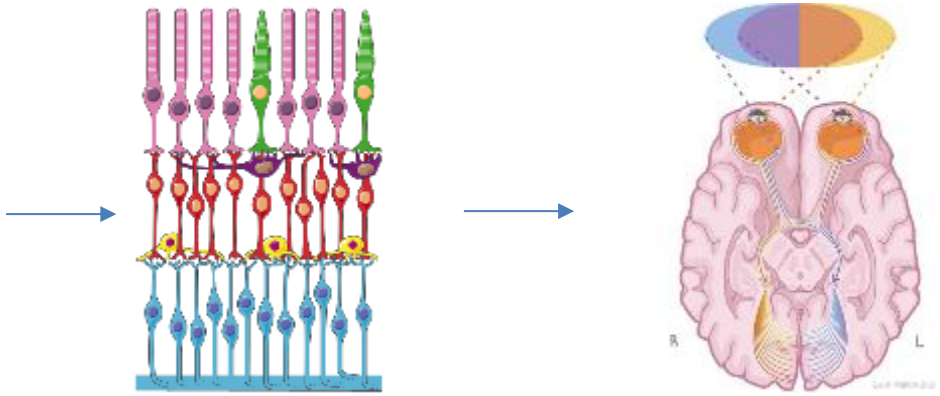
Retinal prosthesis ?
Can electronics replace part of retinal function?
Not Photoreceptors needed

Can Electronics Replace Part of the Retina?

How does a retinal prosthesis work?



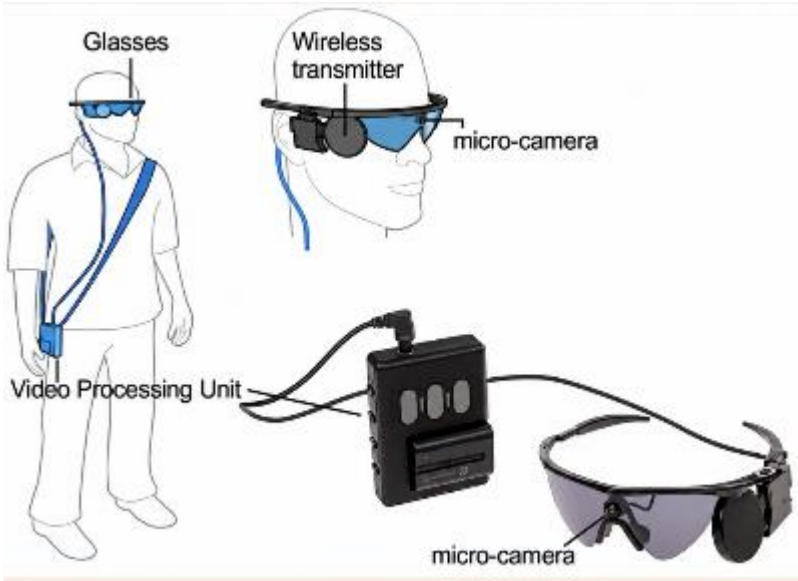
Camera　　Video processor　　Electrode array on retina



Retinal neurons stimulated　　Optic nerve

The camera does not "see for the brain."
It converts visual information into electrical stimulation.

Argus II Retinal Prosthesis



60 electrodes电极
6 × 10 array电极阵列

Argus II was clinically implanted, but the program was later discontinued.

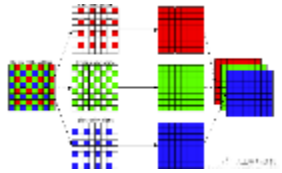
Reddy, V.Ket al. *Advances in Ophthalmology & Visual System*

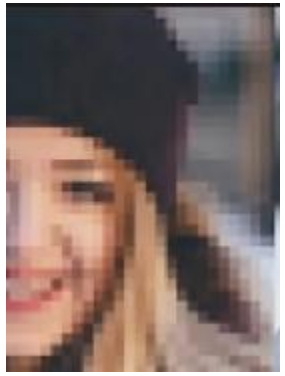
What does artificial vision actually look like?

What we might imagine





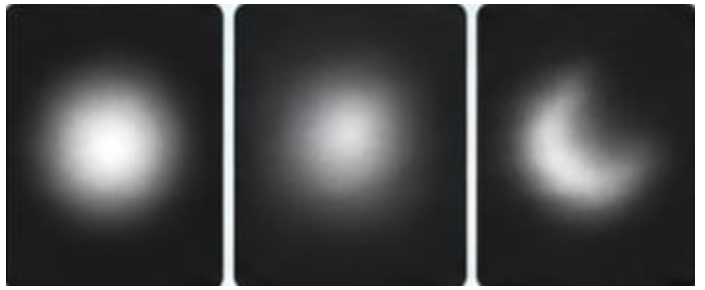




camera image electrode grid perfect low-resolution image?

What is actually perceived?

Phosphene
phosphene 指的是视觉系统受到人工刺激后产生的主观光觉，常表现为亮点、亮斑或不规则形状。



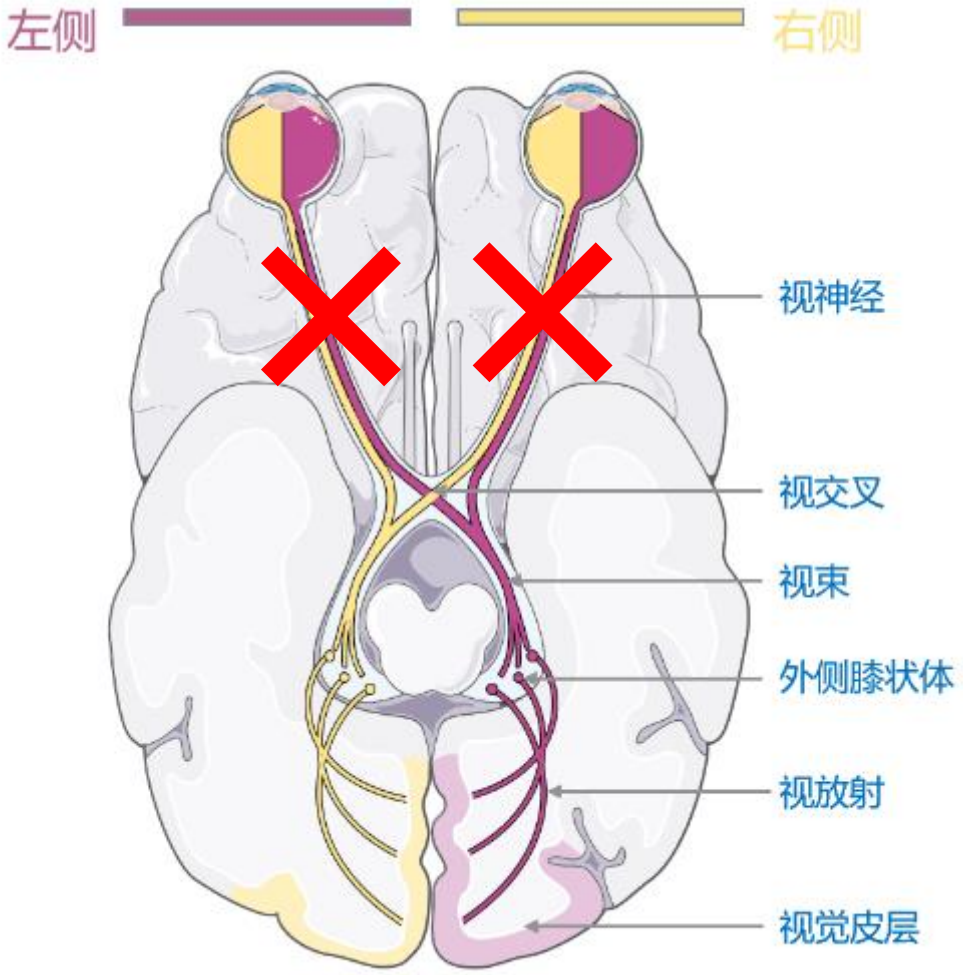
An electrode stimulates neurons, not pixels.

Prosthetic vision is not a screen

1.One electrode activates a population of neurons
2. It may activate axons as well as cell bodies
3. Percepts depend on stimulation parameters and neural anatomy

- Where does vision go wrong?
- When photoreceptors fail, can we provide visual input to the brain in new ways?
- Can we bypass the eyes and stimulate the brain to create vision?

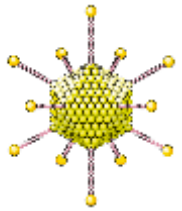
What If the Eye Cannot Talk to the Brain?



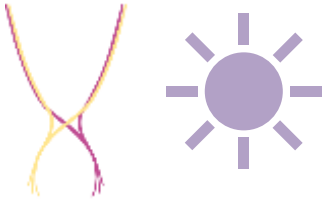
Skip the eye ！

Retinal approaches require a functional downstream pathway

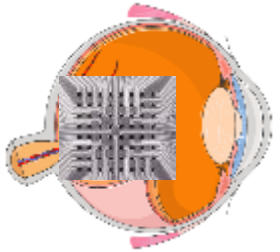
Gene therapy



Optogenetics



Retinal prosthesis

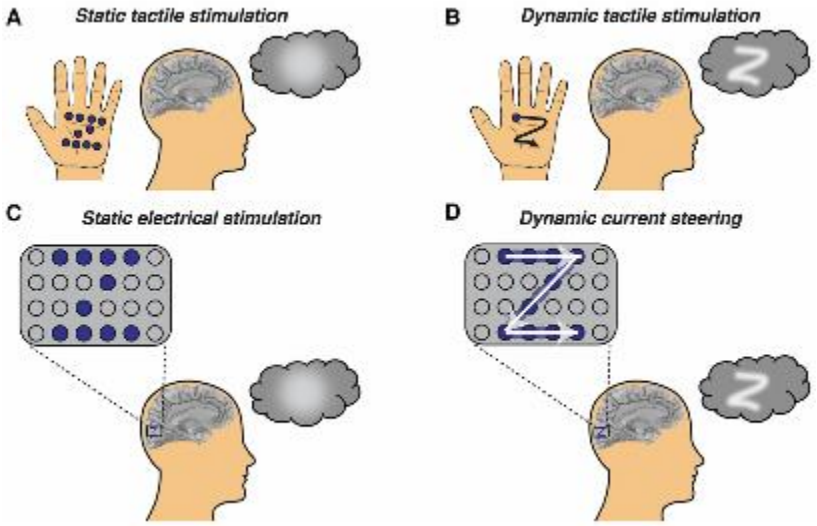


If the signal cannot leave the eye, repairing the retina may not be enough

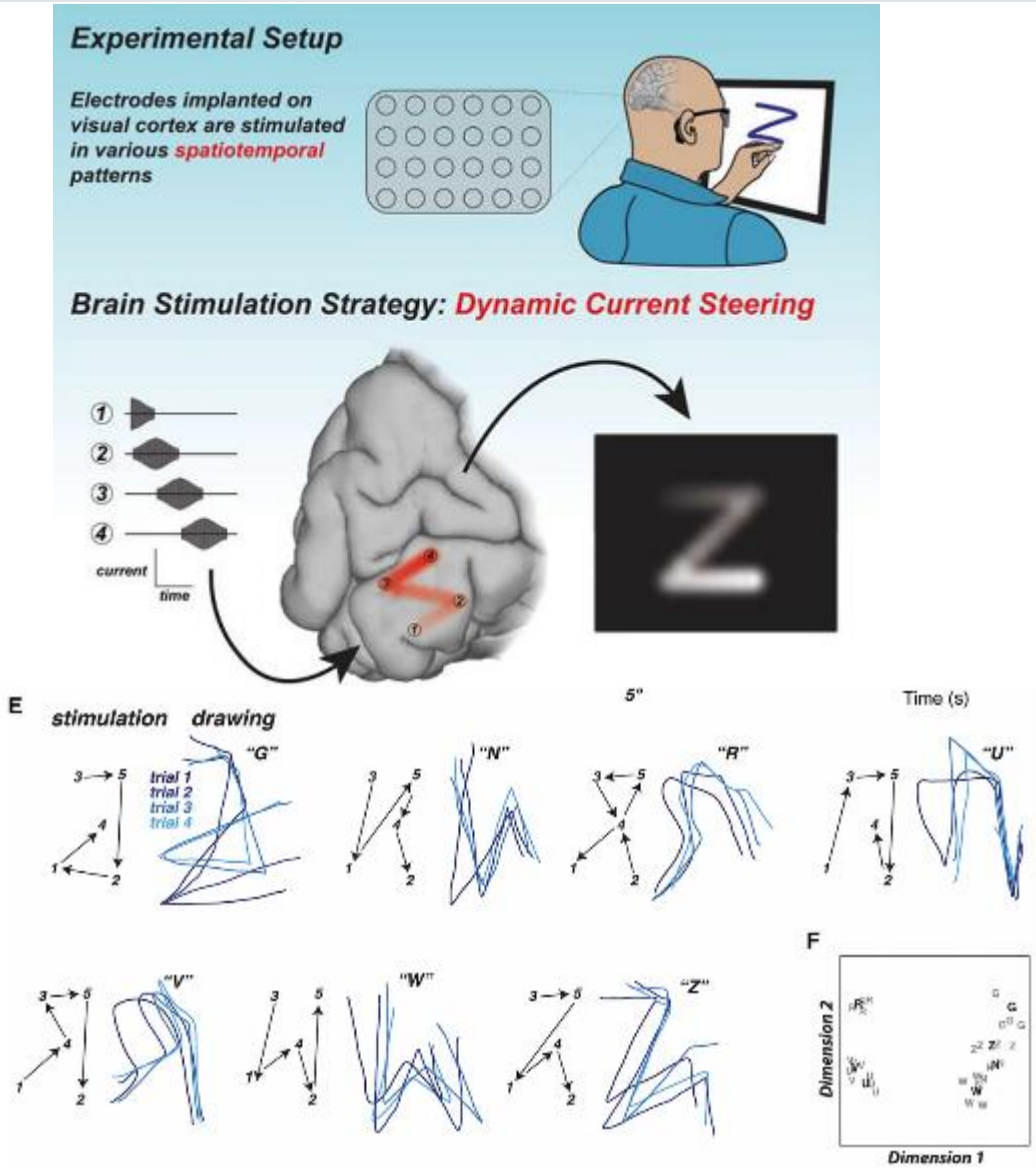
Cortical Visual Prosthesis

If retinal output cannot reach the brain, stimulation must move downstream

Old idea vs New idea



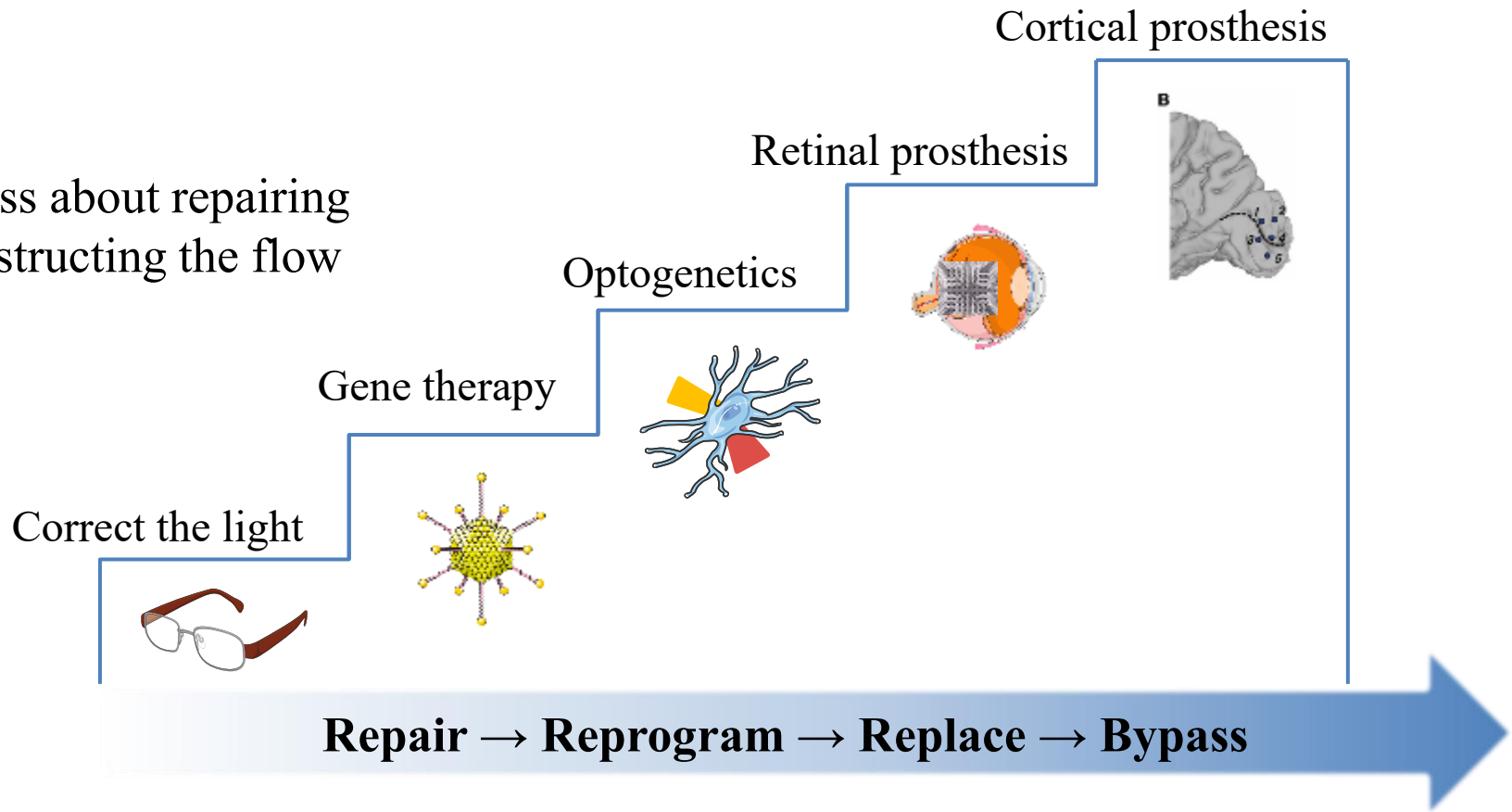
1. Worked in both sighted and blind participants
2. Could identify or reproduce letter-like shapes
3. Perceived structured forms Up to 86 forms/min



Beauchamp MS et al. Cell. 2020 May 14;181(4):774-783.e5.

What Are We Really Restoring?

Restoring sight is becoming less about repairing the eye, and more about reconstructing the flow of visual information.

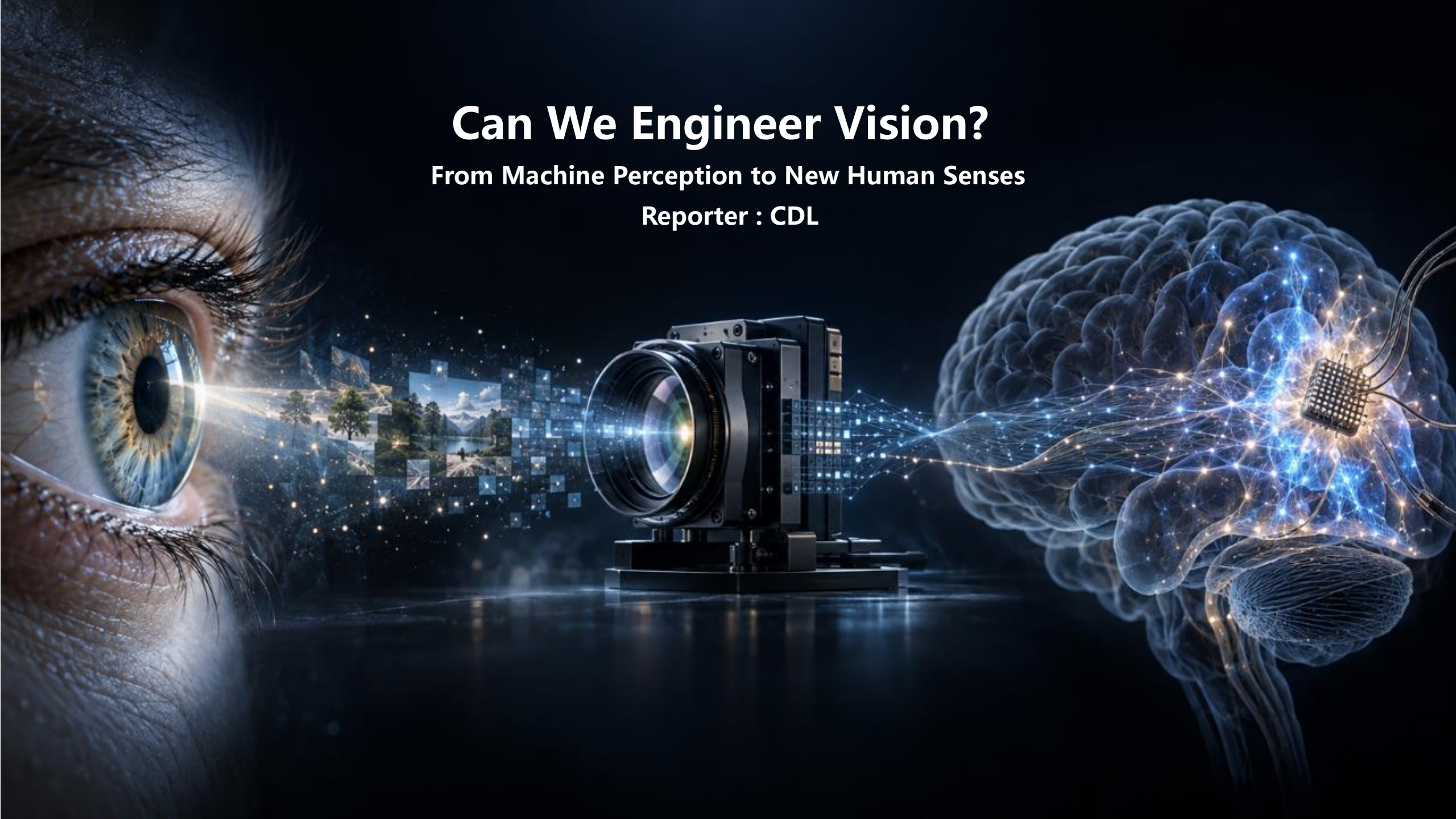


Are we restoring the eye or reconstructing visual experience?

Can We Engineer Vision?

From Machine Perception to New Human Senses

Reporter : CDL



- If machines can see, do they see like us?
- Must visual information enter through the eyes?
- Can we see what nature never gave us?

Seeing Is More Than Naming



Recognition

这是什么?

Action

手应该伸向哪里、张多大?

Experience

它在我看来是什么样子?

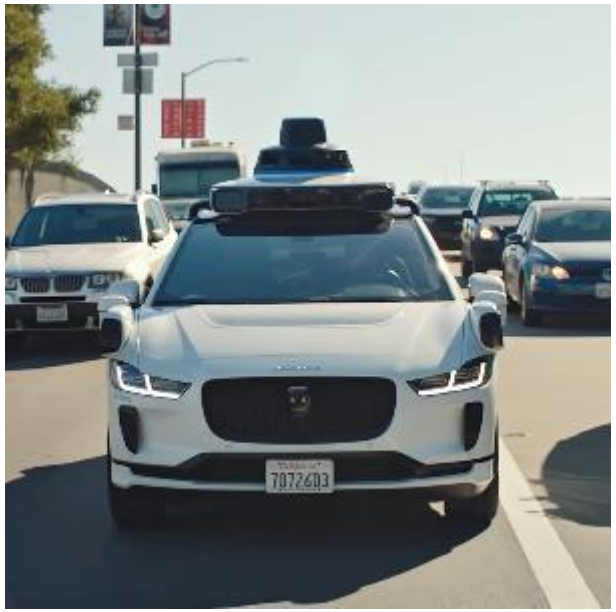
视觉同时支持识别、行动和主观体验。

Engineered Vision Is Already Around Us



手机识别

识别文字与物体



辅助驾驶

发现行人与车辆



VR

让虚拟场景产生真实反应

Vision Guides Action

Sense, Solve, and Go: The Magic of the Waymo Driver

Perception

发现行人

↓

Prediction

预测路径

↓

Decision

决定减速

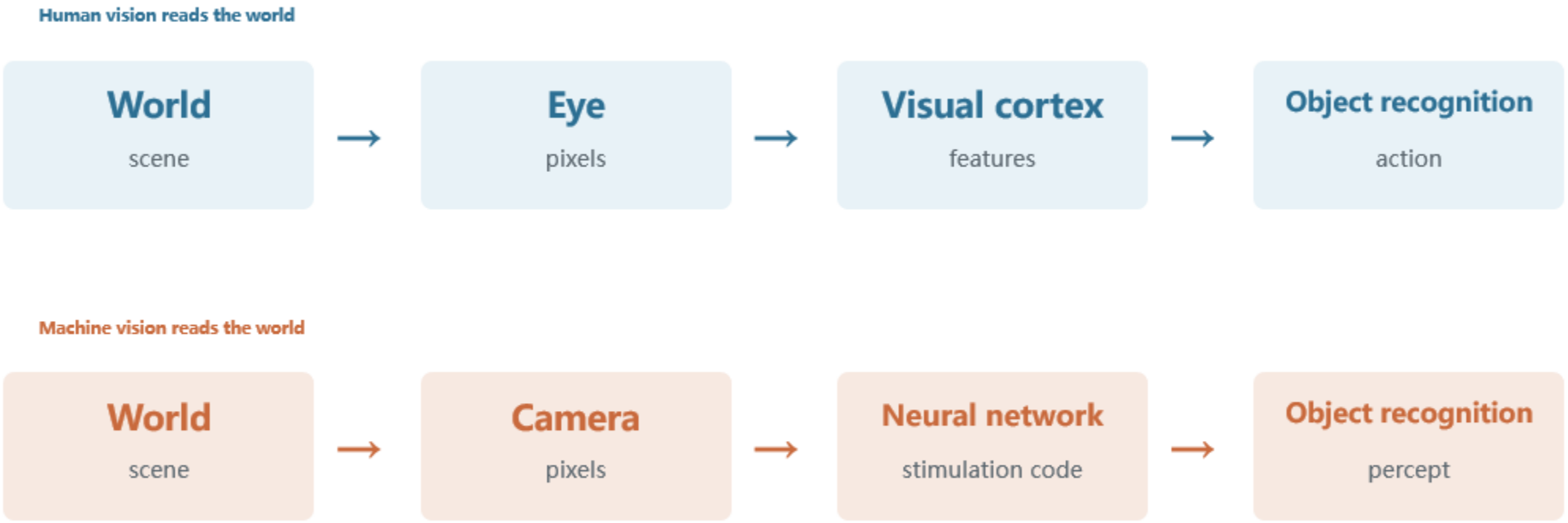
↓

Action

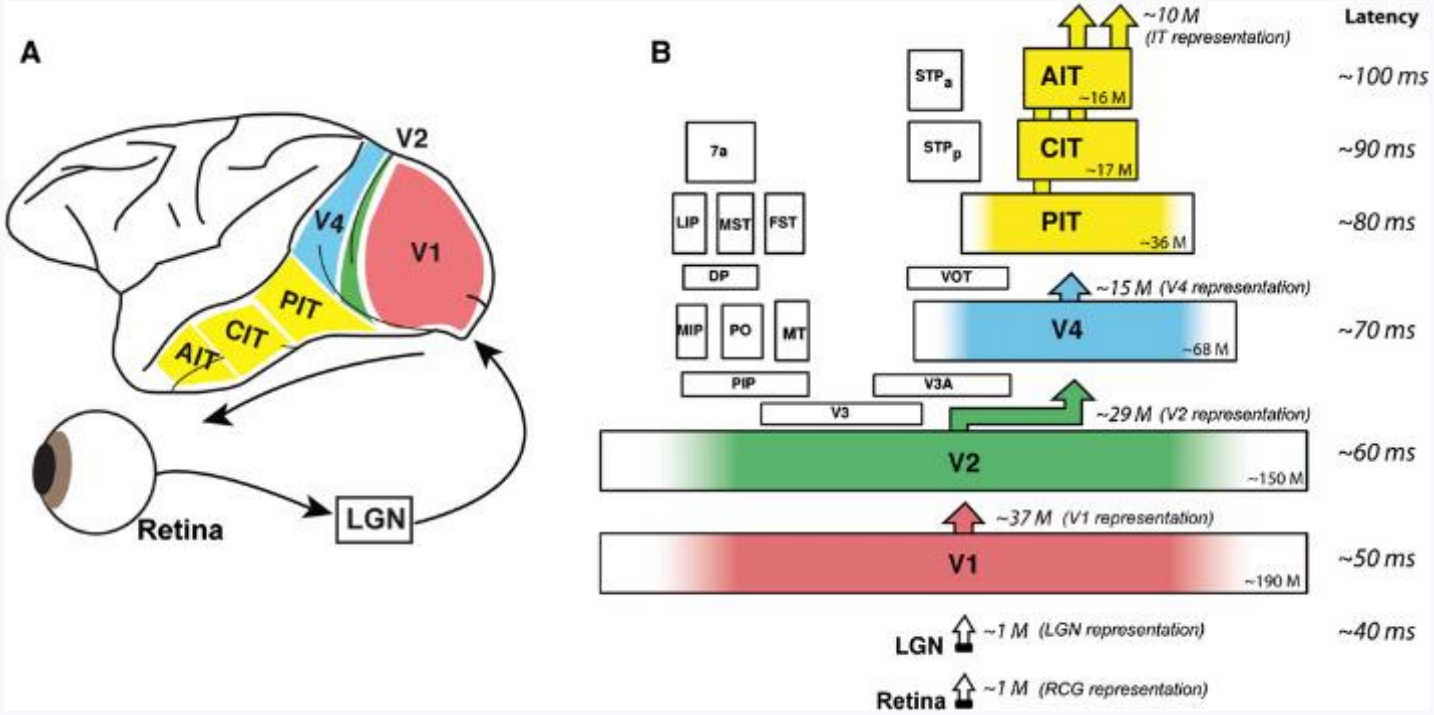
刹车

视觉的价值体现在及时指导行为。

If a Machine Can See, Does It See Like Us?



The Ventral Visual Pathway



V1:局部边缘、线条、朝向、空间频率等

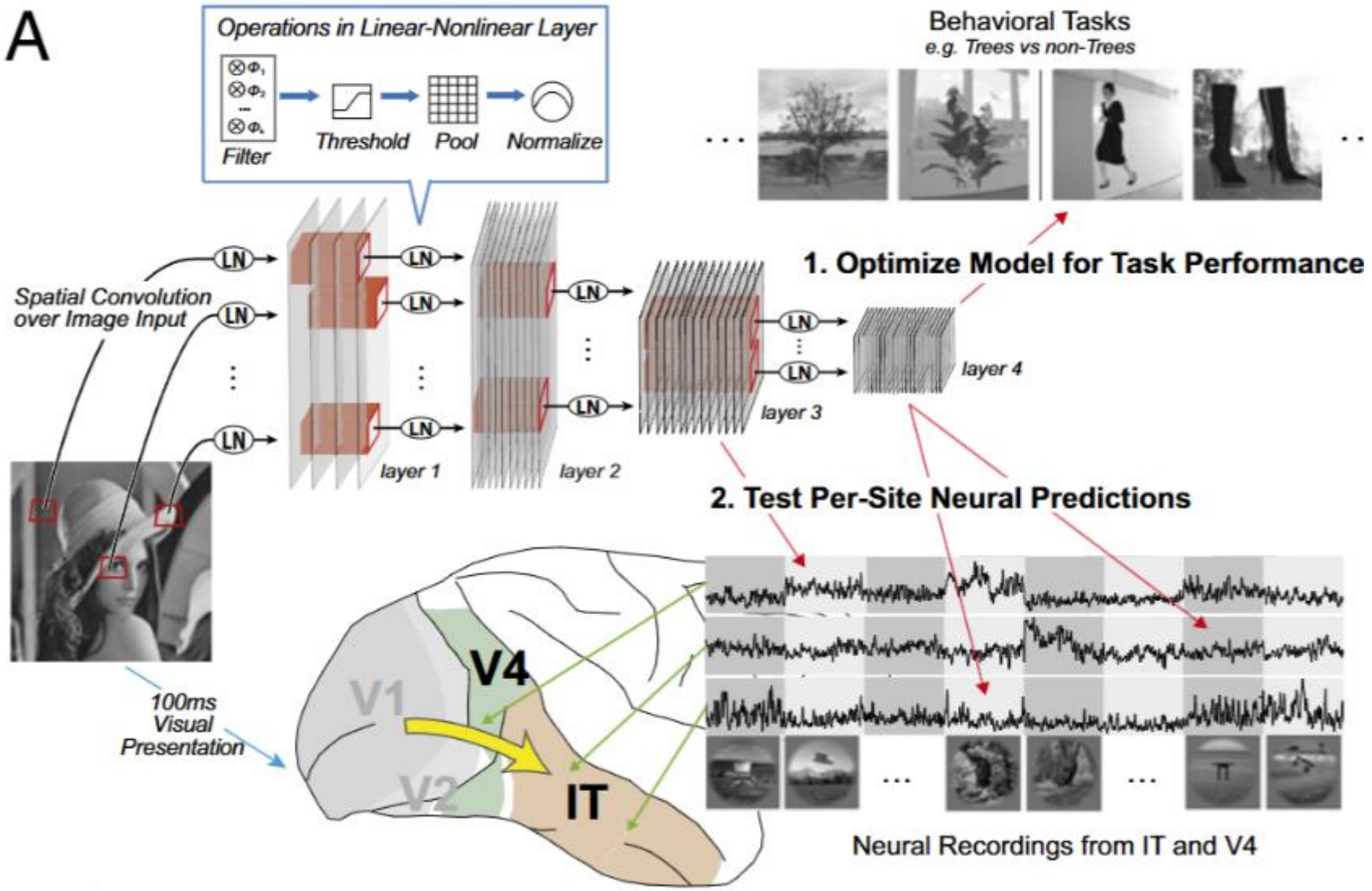
V2:轮廓、纹理、图形—背景关系等更复杂组合

V4:颜色、曲率、较复杂形状和表面特征

IT:复杂物体表征、类别和物体识别

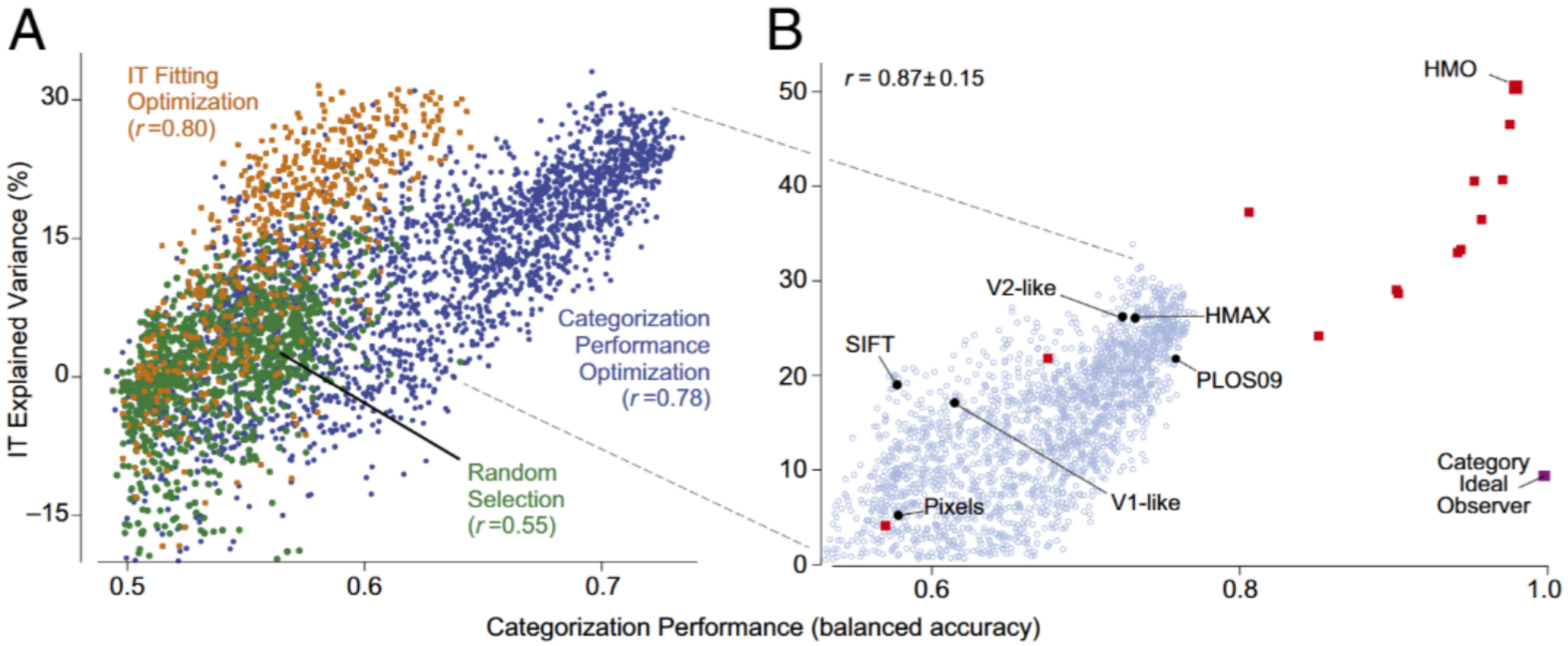
DiCarlo JJ et al. (2012) Neuron 73(3):415–434, Figure 3 (p.419)

Better Recognition Models Better Predict IT Cortex



Yamins, Daniel L K et al. *PNAS* vol. 111,23 (2014):

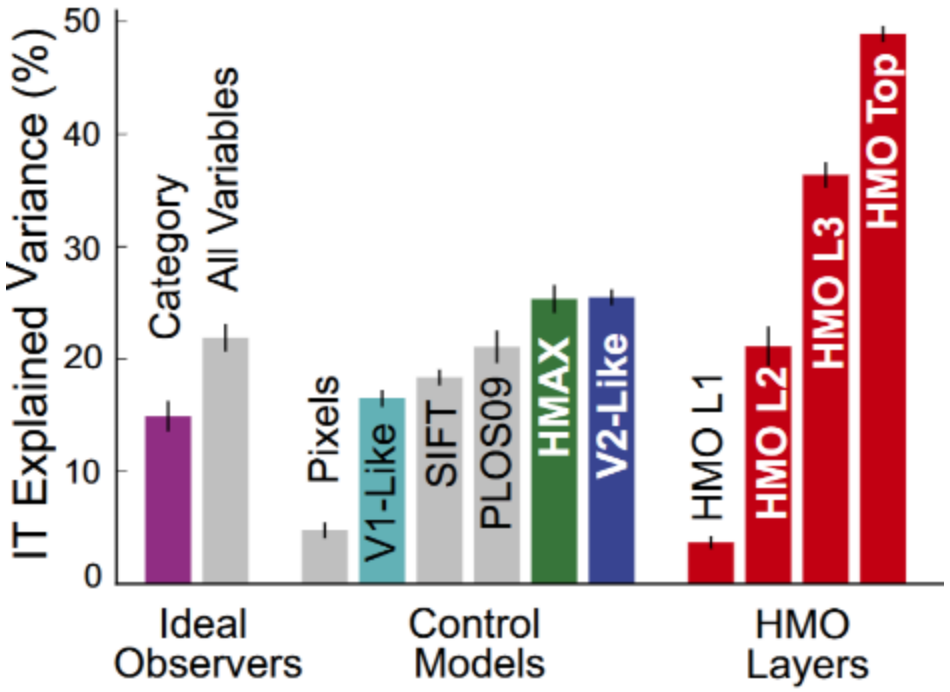
Task Optimization Can Produce Brain-Like Representations



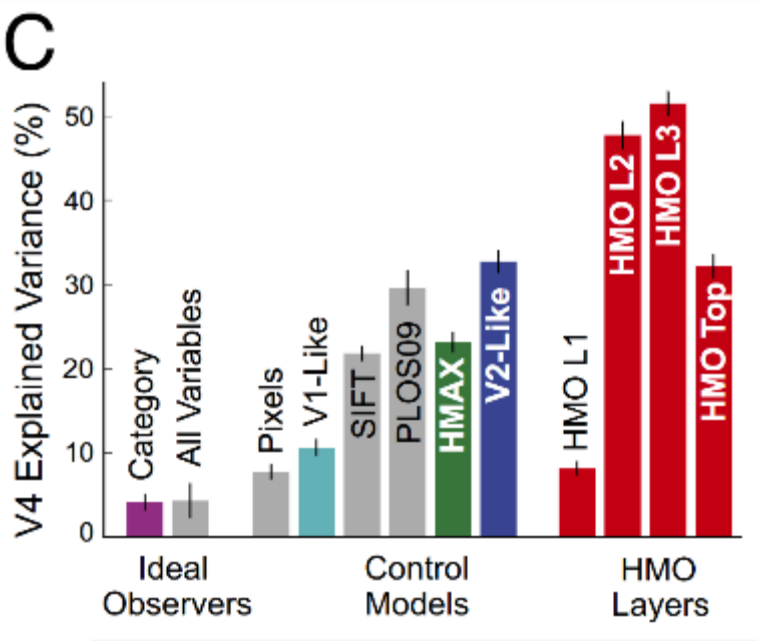
一个神经网络越擅长复杂物体识别，通常就越能预测 IT 神经活动

Yamins, Daniel L K et al. *PNAS* vol. 111,23 (2014):

Machine and Human Vision Are Similar—but Not Identical



Top--IT



L3—V4

人工神经网络与腹侧视觉通路呈现层级对应关系

Yamins, Daniel L K et al. *PNAS* vol. 111,23 (2014):

Machines May Rely on Different Visual Evidence



(a) Texture image

81.4%	**Indian elephant**
10.3%	indri
8.2%	black swan



(b) Content image

71.1%	**tabby cat**
17.3%	grey fox
3.3%	Siamese cat



(c) Texture-shape cue conflict

63.9%	**Indian elephant**
26.4%	indri
9.6%	black swan

你看到的是猫，还是大象?

Human observers

更依赖整体形状

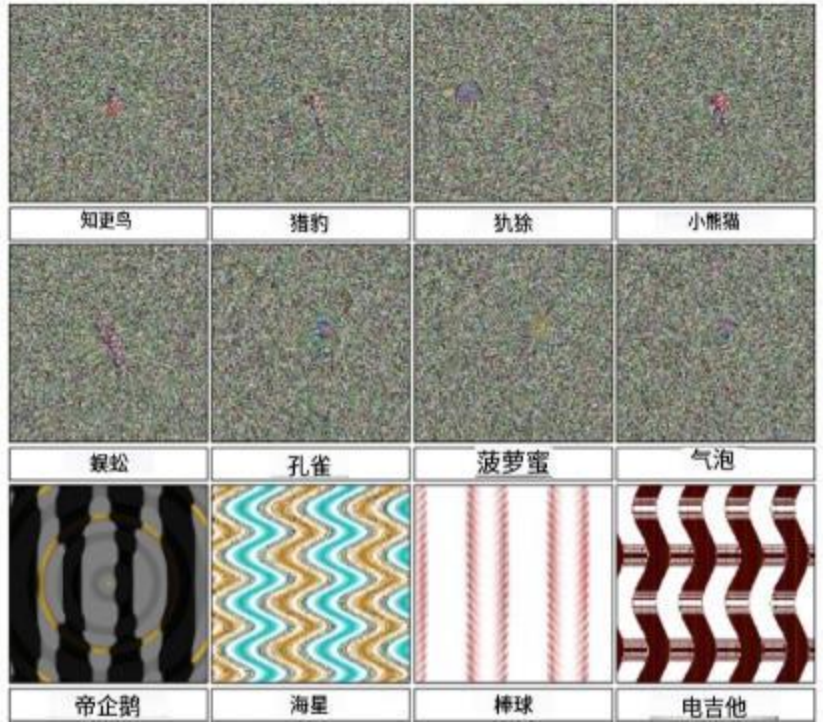
Classic ImageNet CNNs

更容易依赖局部纹理

Geirhos et al., 2019

Machines May Rely on Different Visual Evidence





相同标签可以来自不同的视觉证据。

Task-Relevant Information Can Travel Through Different Channels



Light	———	retina
Sound	———	auditory pathway
Touch	———	somatosensory pathway
Stimulation	———	visual cortex

Does the brain need the original sensor, or the useful structure in the signal?

Visual Structure Can Be Recoded as Sound

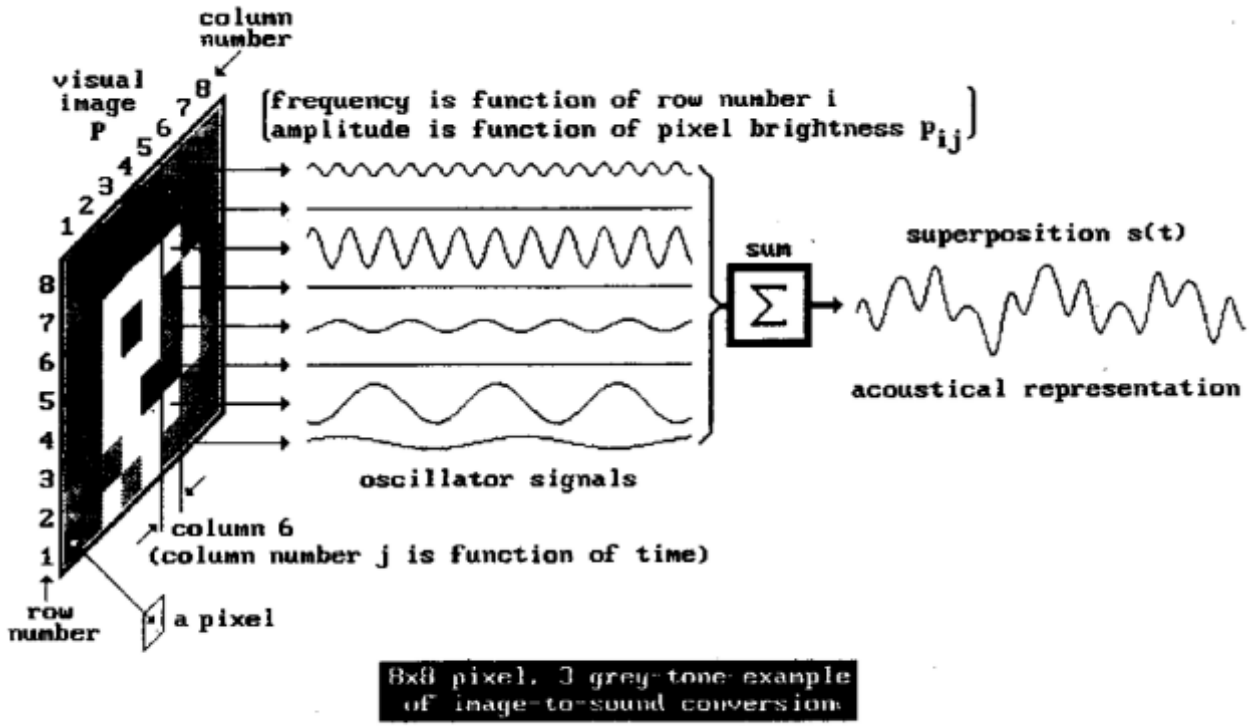


Fig. 1. Principles of the image-to-sound mapping.

Left to right

扫描时间

Height

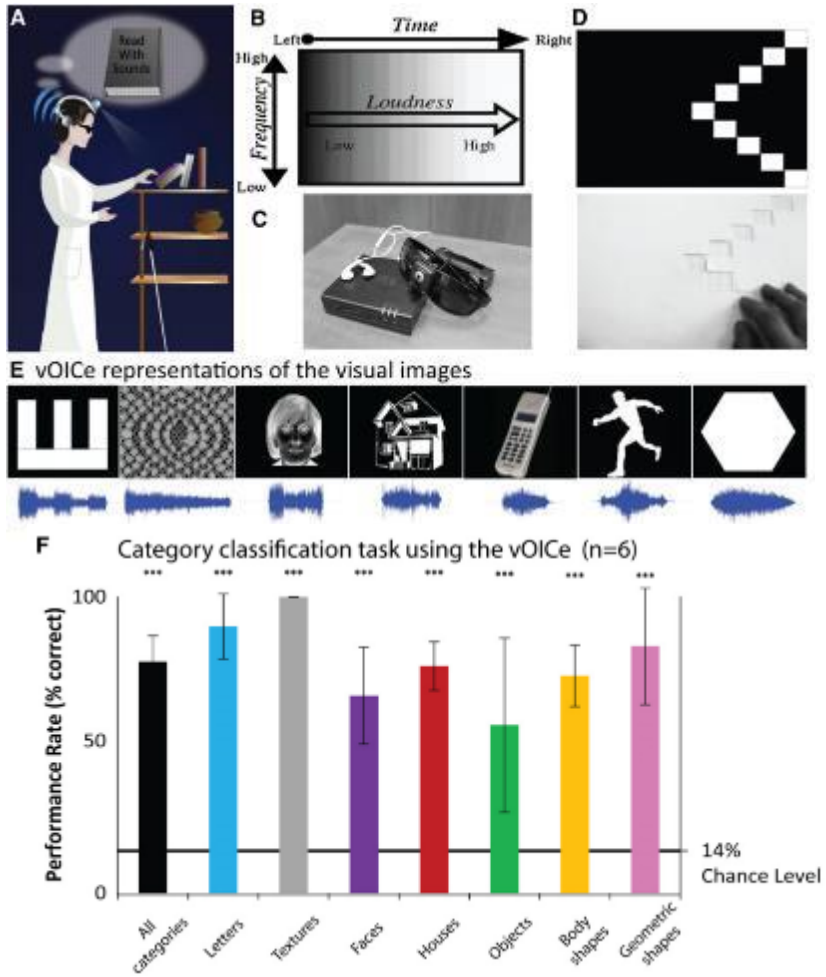
音调高低

Brightness

音量高低

Meijer, P. B. L. (1992). *IEEE Transactions on Biomedical Engineering*, *39*(2), 112–121.

Sensory Substitution Codes Can Be Learned



VWFA（Visual Word Form Area，视觉词形区）

先天全盲成人

用 soundscapes 识别文字和复杂图像

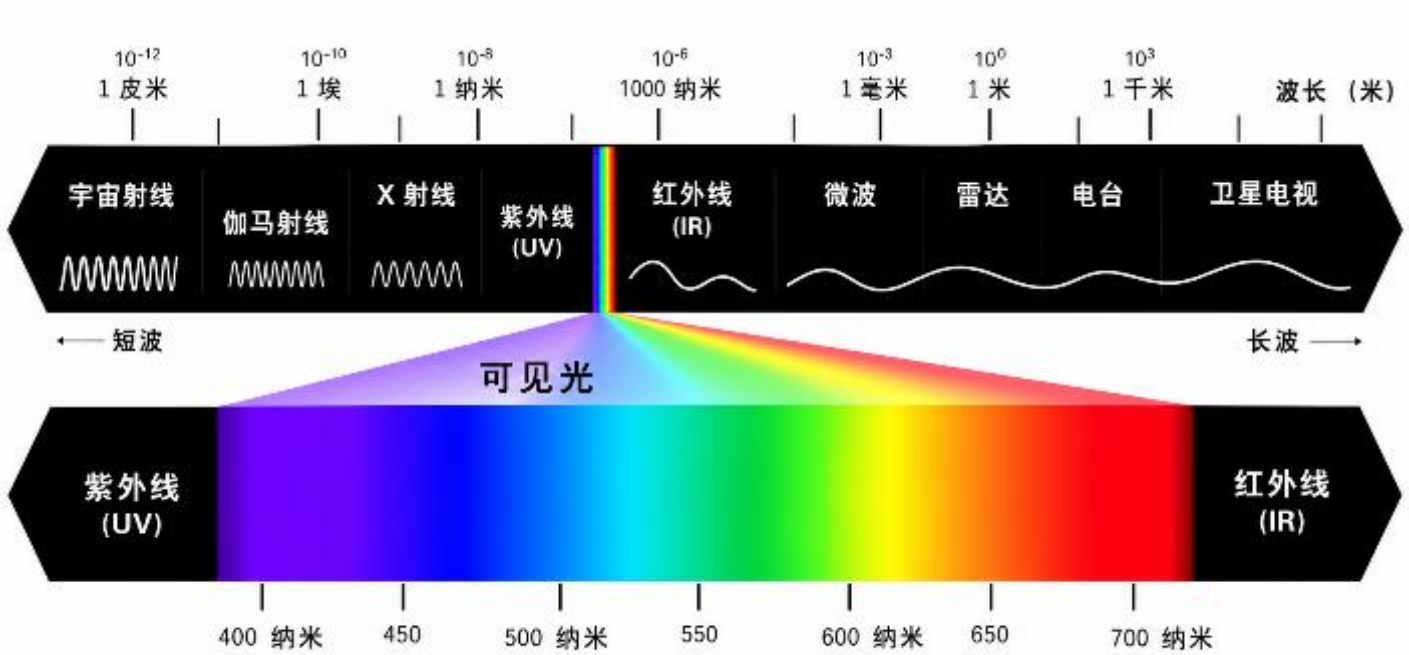
处理字母 soundscapes 时

VWFA 表现出选择性激活

声音携带的是字形结构，而不是语言声音。

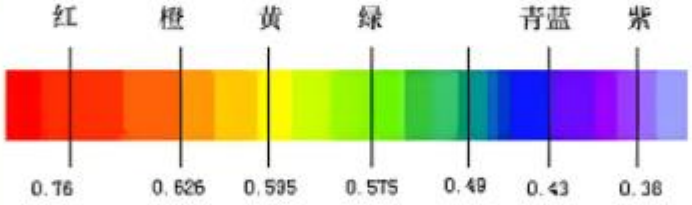
Striem-Amit, Ella et al. *Neuron* vol. 76,3 (2012): 640-52.

- If machines can see, do they see like us?
- Must visual information enter through the eyes?
- **Can we see what nature never gave us?**

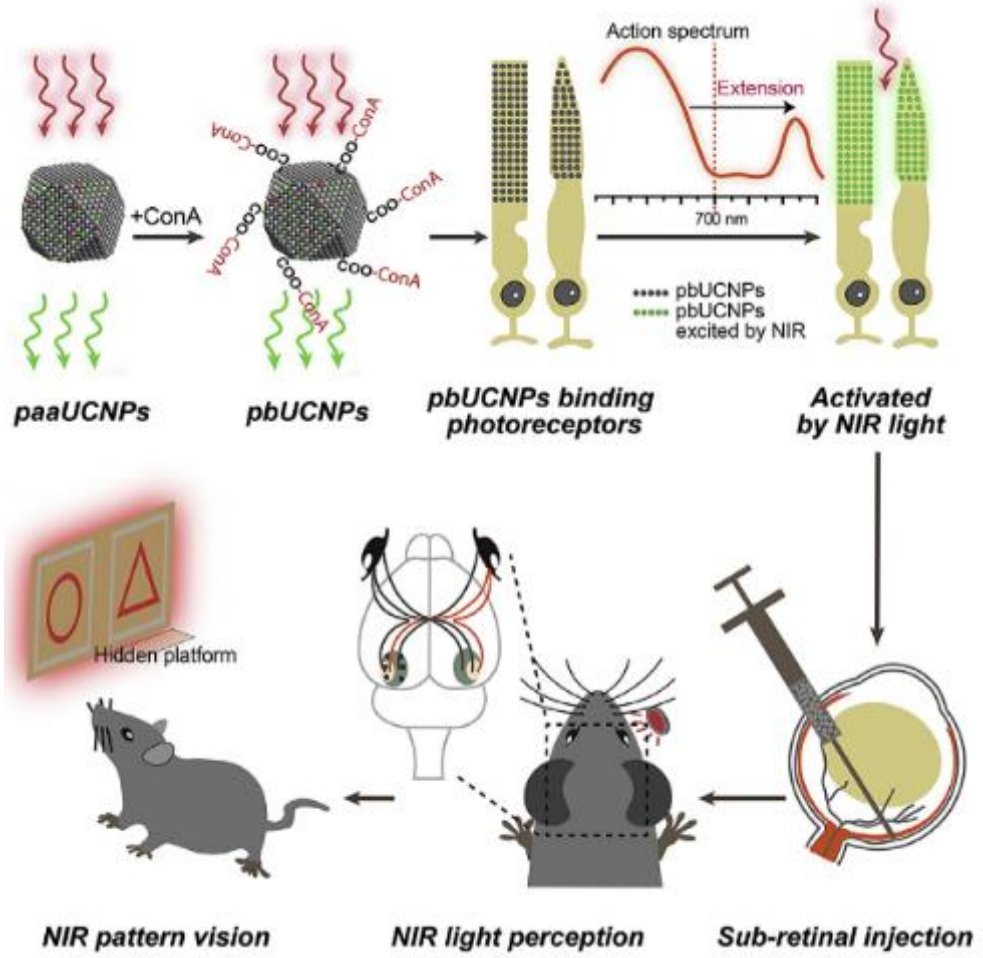


电磁波谱 · 光谱

太阳光总辐射

		不可见光（红外区域）			可见光	不可见光（紫外区域）		
无线电波	微波	远红外线	中红外线	近红外线		紫外线	X 射线	γ 射线
波长>1 毫米		波长：1 毫米-5.6 微米	波长：5.6-0.76 微米		波长：0.76-0.38 微米	波长：0.38 - 0.2 微米	波长< 0.2 微米	

Another Strategy: Expand the Native Retina



980 nm NIR

pbUCNPs与光感受器结合，将近红外光子转化为可见光。

NIR pattern vision

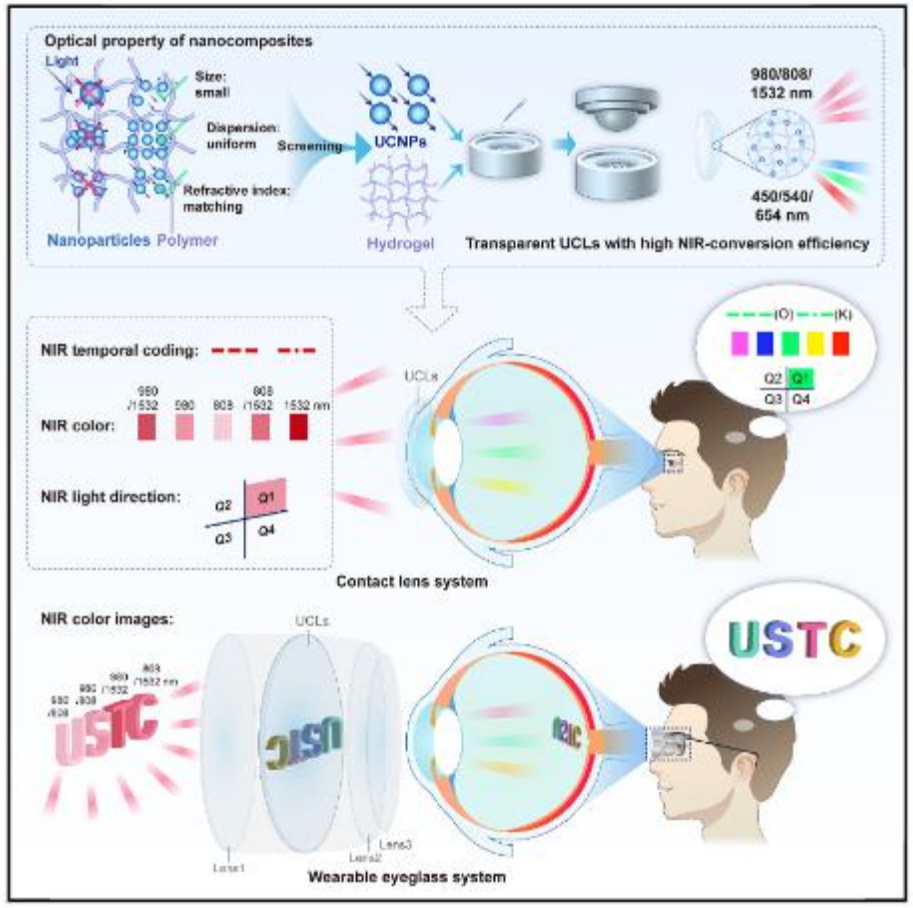
在使用添加的近红外通道时，小鼠保持正常的日光视力。

NIR
nearinfrared
pbUCNPs
photoreceptor-binding upconversion nanoparticles
感光细胞结合型上转换纳米颗粒

Ma, Yuqian et al. *Cell* vol. 177,2 (2019): 243-255.e15.

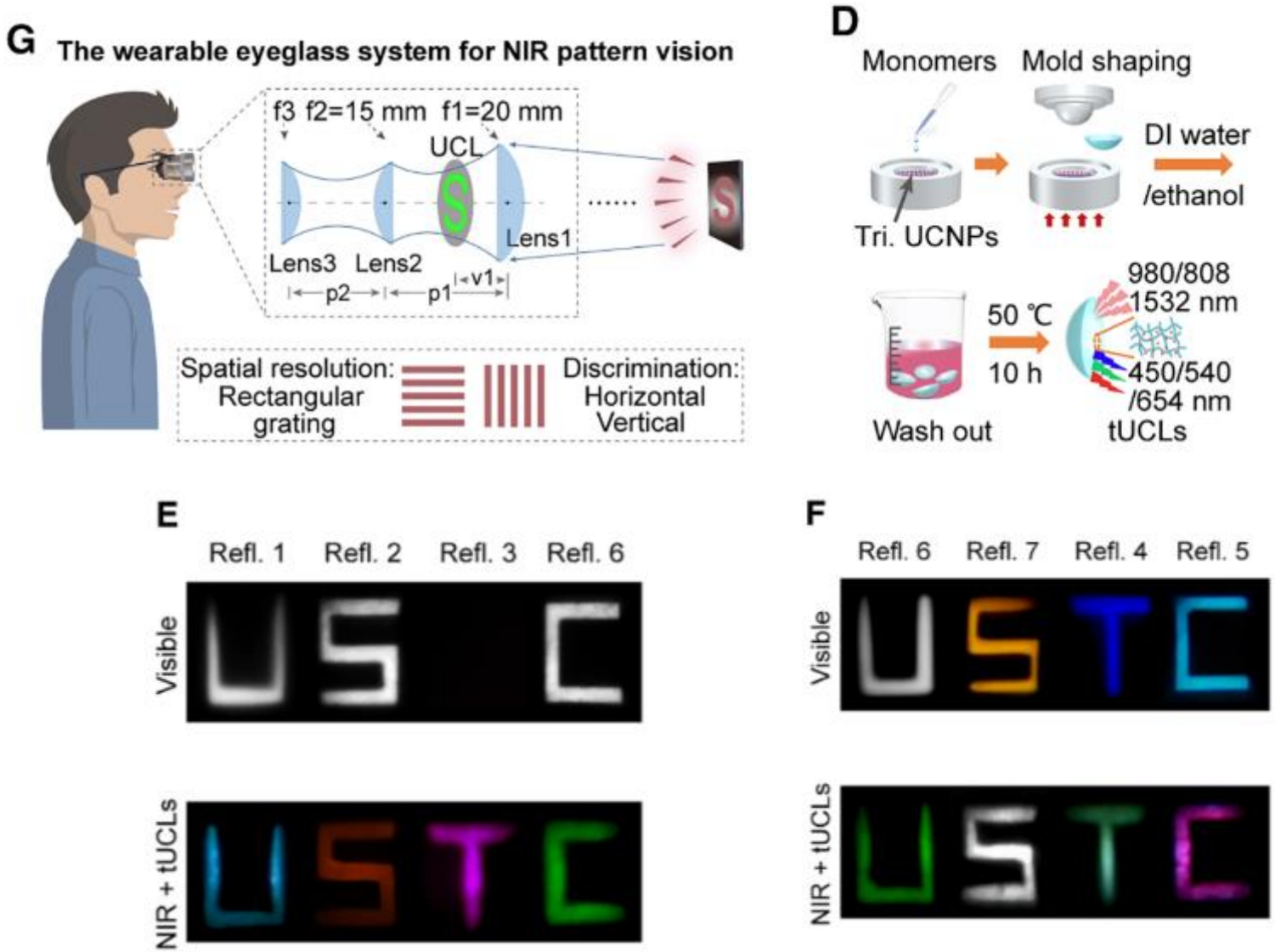
NIR Vision Progressed from Injection to Wearable Lenses





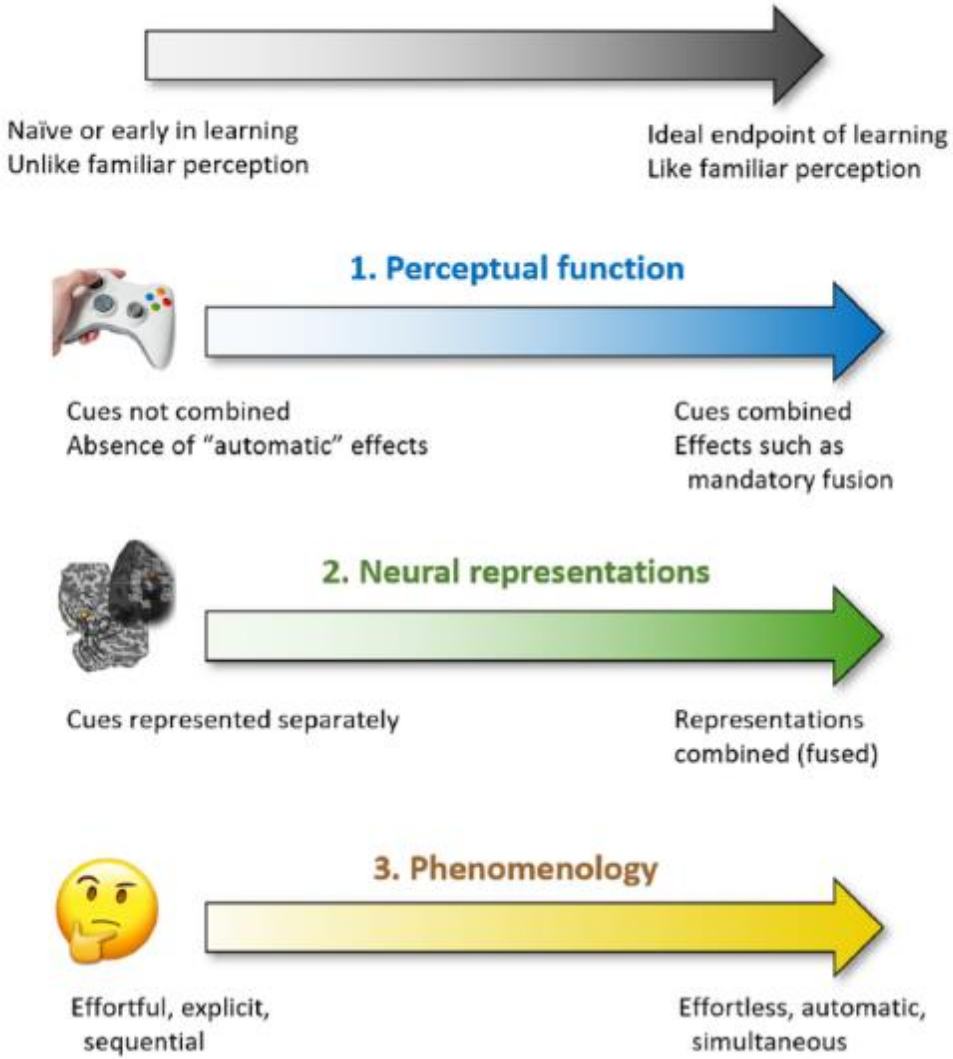
Ma, Yuqian et al. *Cell* vol. 188,13 (2025): 3375-3388.e18.

Humans Can Decode NIR Temporal and Spatial Information



Ma, Yuqian et al. *Cell* vol. 188,13 (2025): 3375-3388.e18.

When Does a New Signal Become a New Sense?



A useful test has three layers

Perceptual function

Can the signal guide judgments and actions?

Neural representations

Does the brain represent it together with familiar signals?

Phenomenology

Does it become automatic or subjectively perceptual?

Nardini, Marko et al. *Augmented human research* vol. 10,1 (2025): 1.

Future Vision Could Encode More Than Light



Infrared

热源与可见光之外的光谱

Ai labels

人、物体、文字和风险提示

Distance

深度与导航方向

New color axis

新的颜色区分维度

未来的视觉系统可能编码比自然光更多的信息。

Take home message

1. **Visual functions can be achieved in different ways.**

   机器可以完成与人类似的视觉任务，但其内部表征和所依赖的视觉证据未必与人类相同。

2. **Useful information can be rerouted.**

   任务相关信息不一定只能通过眼睛进入；它可以被重新编码，并通过其他感觉通道被学习和利用。

3. **Perception can be expanded beyond natural sensory limits.**

   工程手段已经可以让感觉系统获取天然视觉范围之外的信息，例如 NIR；但“能够使用一种新信号”还不等于真正形成了一种新的主观感官。