

# Multisensory Perception of Self Motion: Psychophysics and Functional Neuroanatomy

Mark W. Greenlee



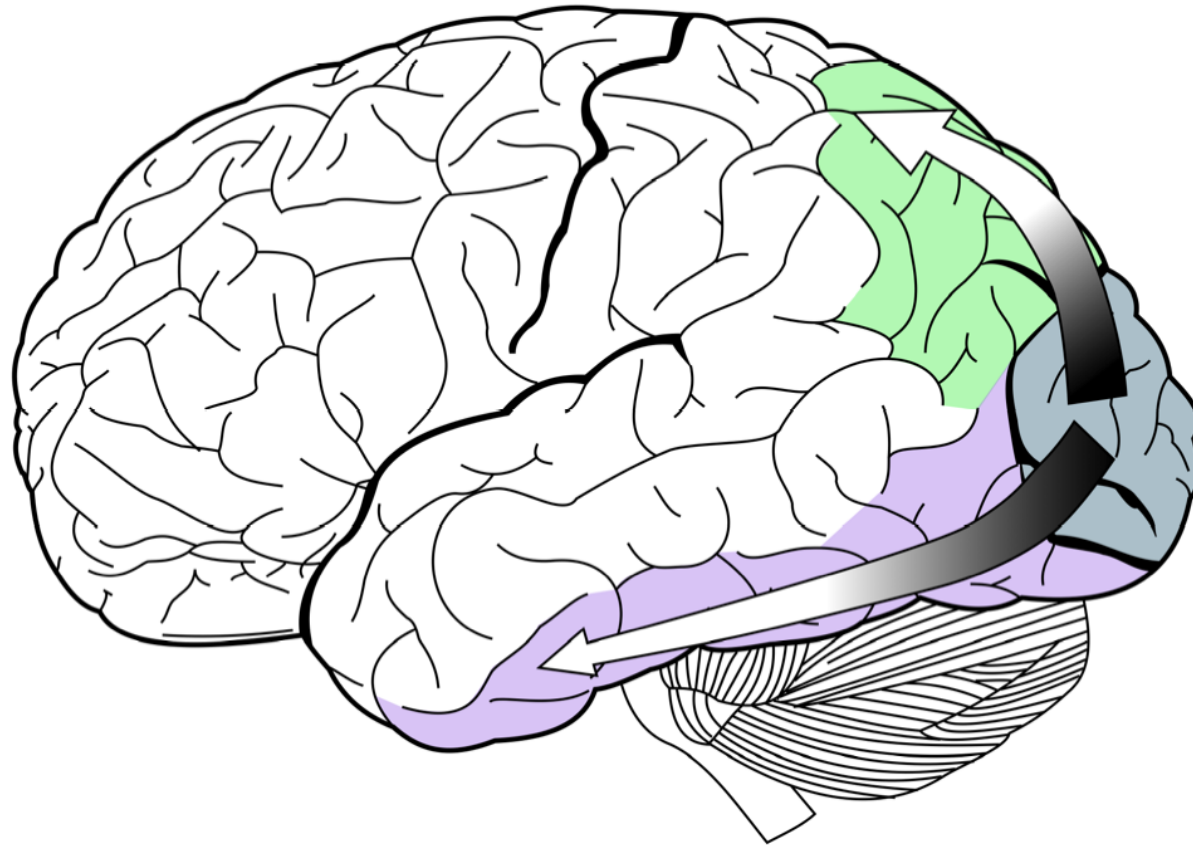
University of Regensburg

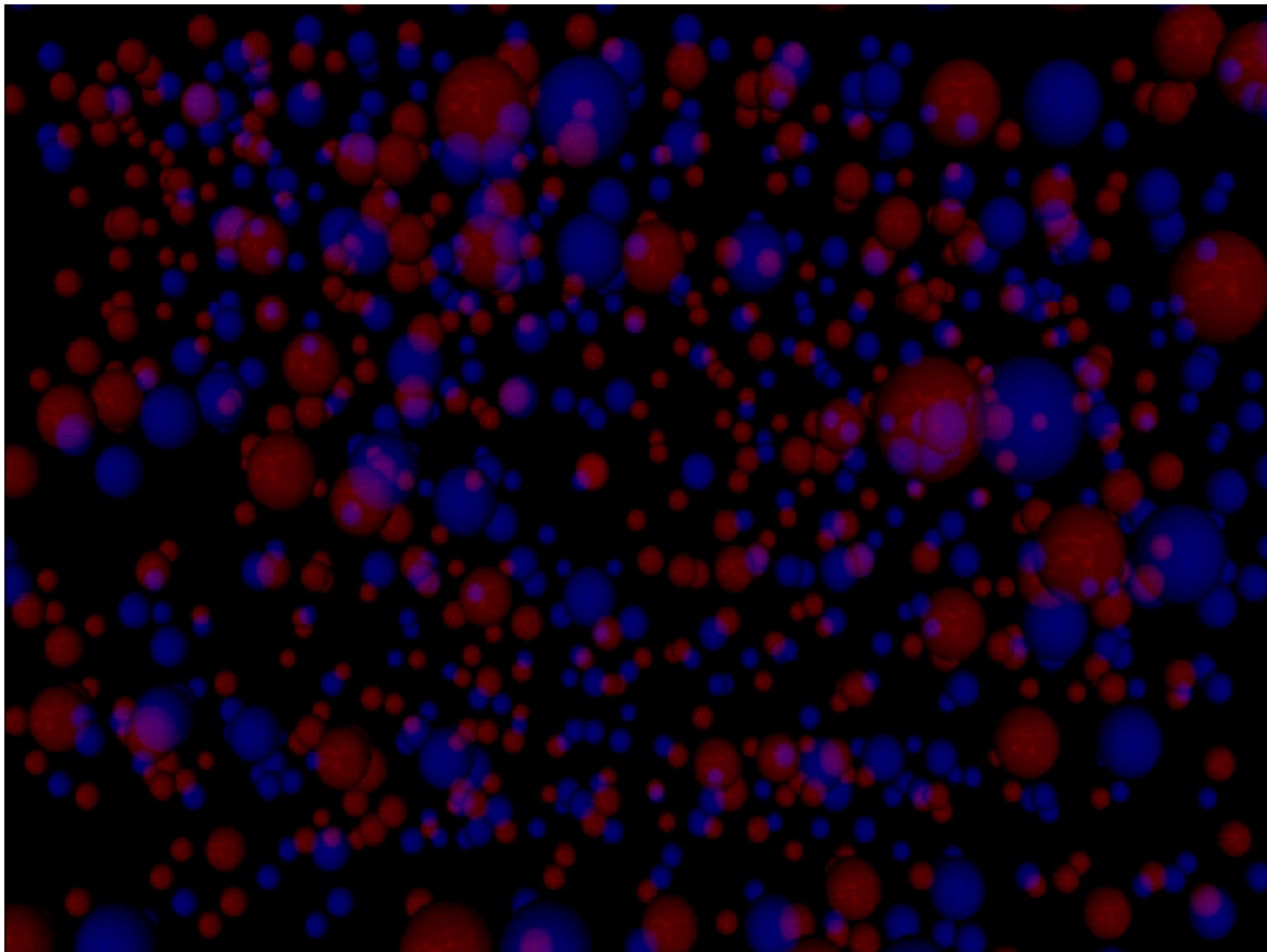
# Optic flow, Eye Movements & Self-motion perception



# Visual Processing

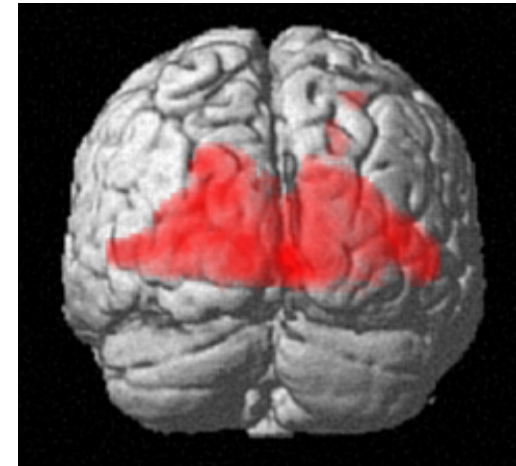
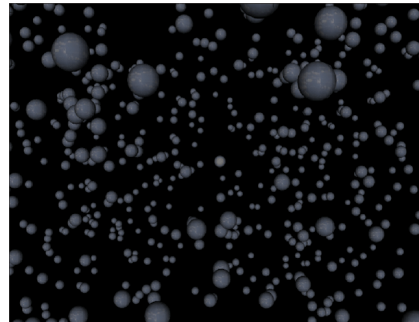
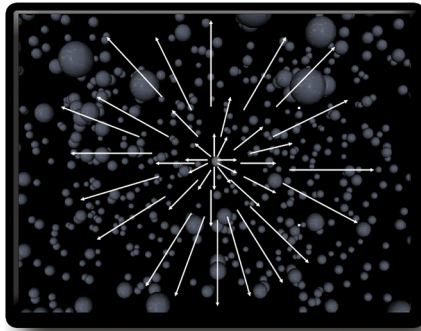
Ventral and dorsal streams



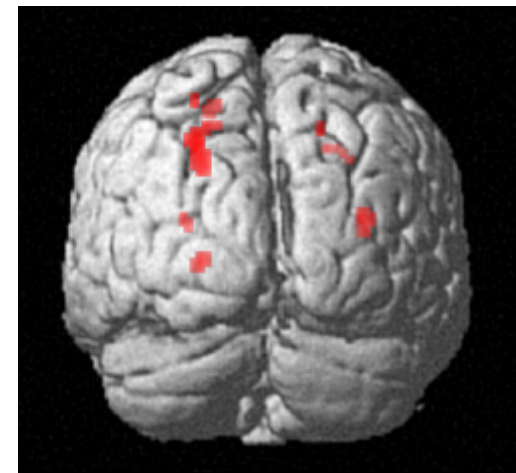
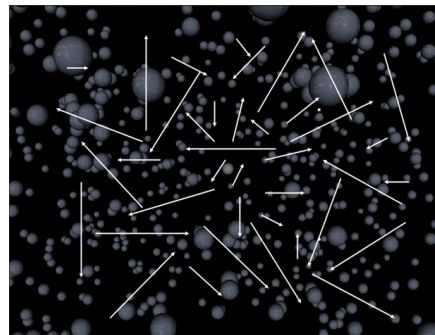
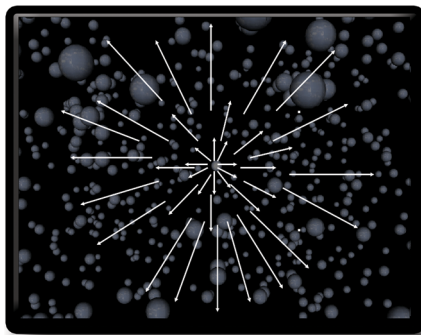


# Region of interest Analysis

Contrast: expansion > static

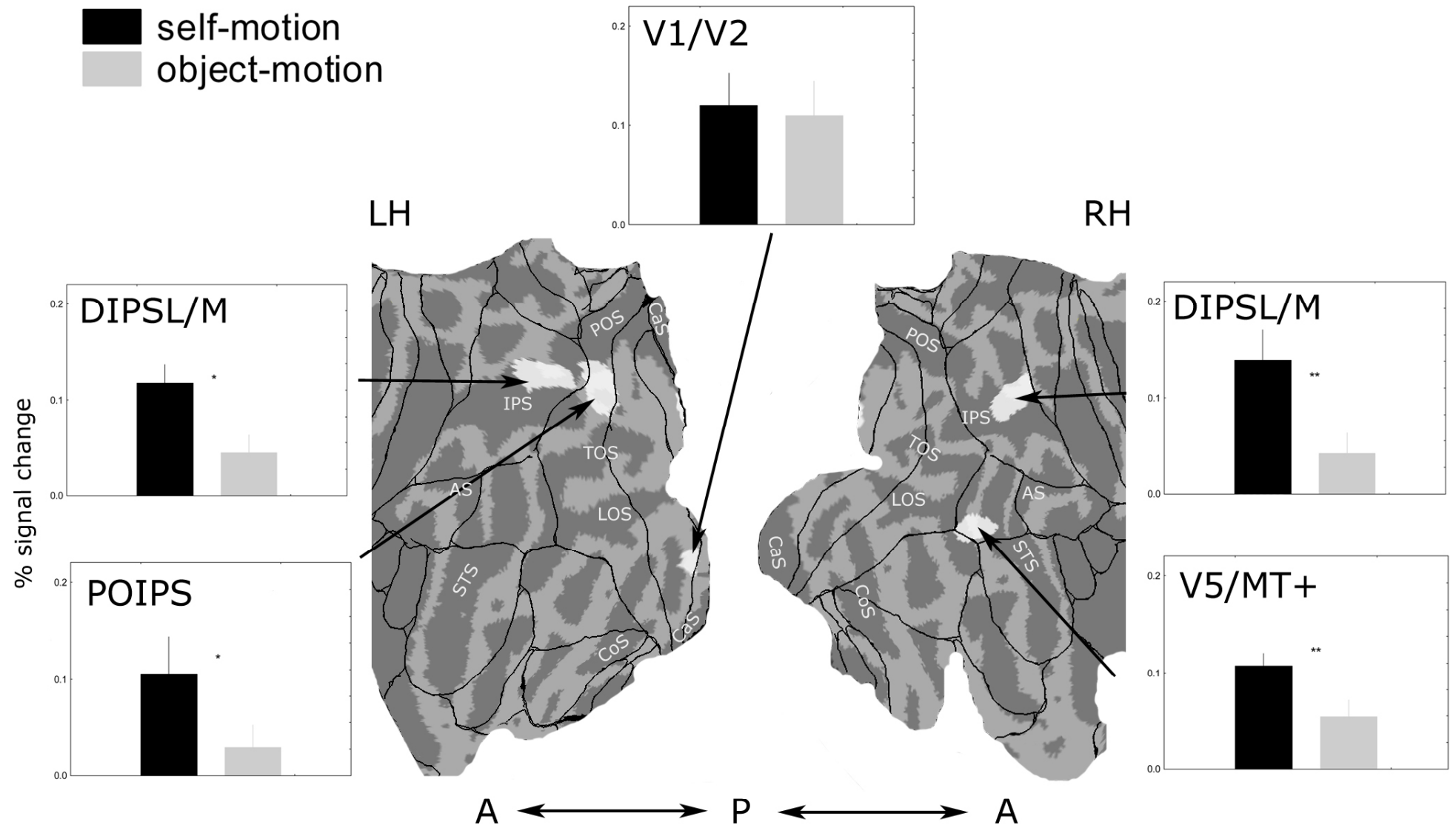


Contrast: expansion > random

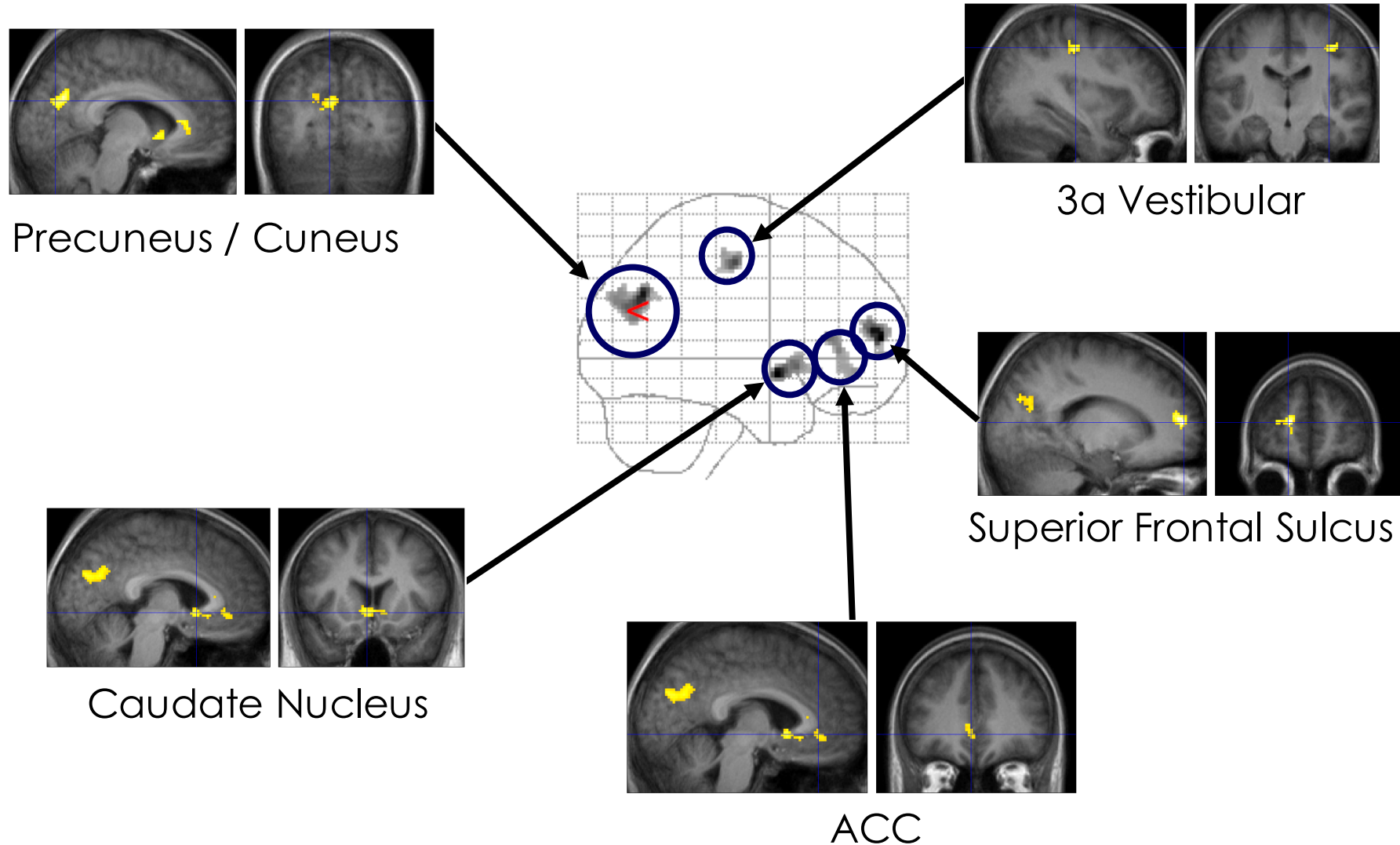


$N = 10$ ;  $p(\text{corrected}) < 0.05$

# Results: Region of interest analysis



# GLM Results:vection vs object-motion

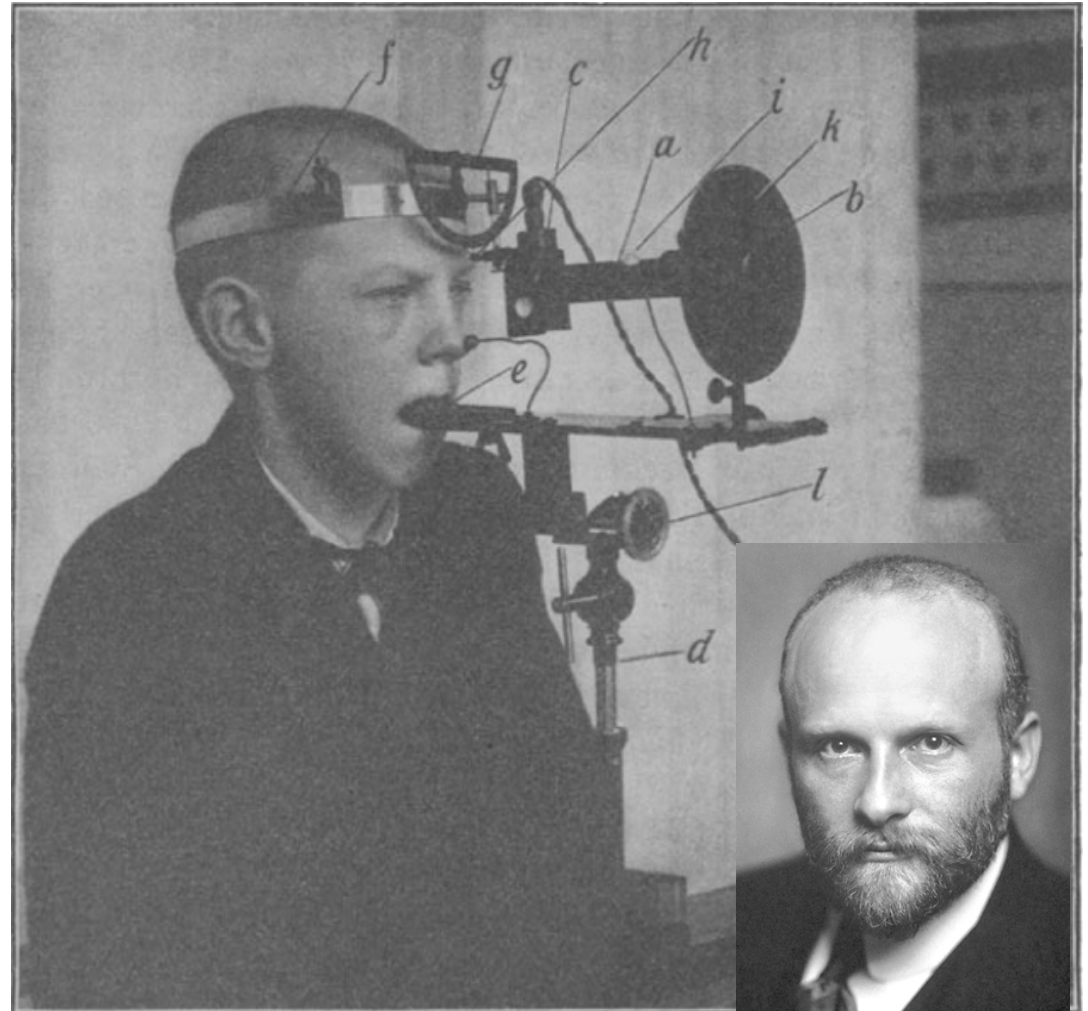


N = 10; p(corrected) < 0.05

Kovacs, Raabe, Greenlee Cerebral Cortex (2008)

# Caloric Nystagmus, Vestibular-ocular reflex

- a) Telescope (50 x mag)
- b) Scale (deg. Visual angle)
- c) Lamp
- d) Support
- e) Bitebar
- f) Head mount
- g) Ruler
- h) Pendulum weight



Robert Bárány: Nobel Prize for Physiology or Medicine in 1914

Robert Bárány (1876–1936)

Bárány, R. (1906). Über die vom Ohrlabyrinth ausgelöste Gegenrollung der Augen bei Normalhörenden, Ohrenkranken und Taubstummen. *European archives of otorhinolaryngology : official journal of the European Federation of Oto-Rhino-Laryngological Societies (EUFOS) : affiliated with the German Society for Oto-Rhino-Laryngology - Head and Neck Surgery*, 68(1-2), 1–30. doi:10.1007/BF01834666



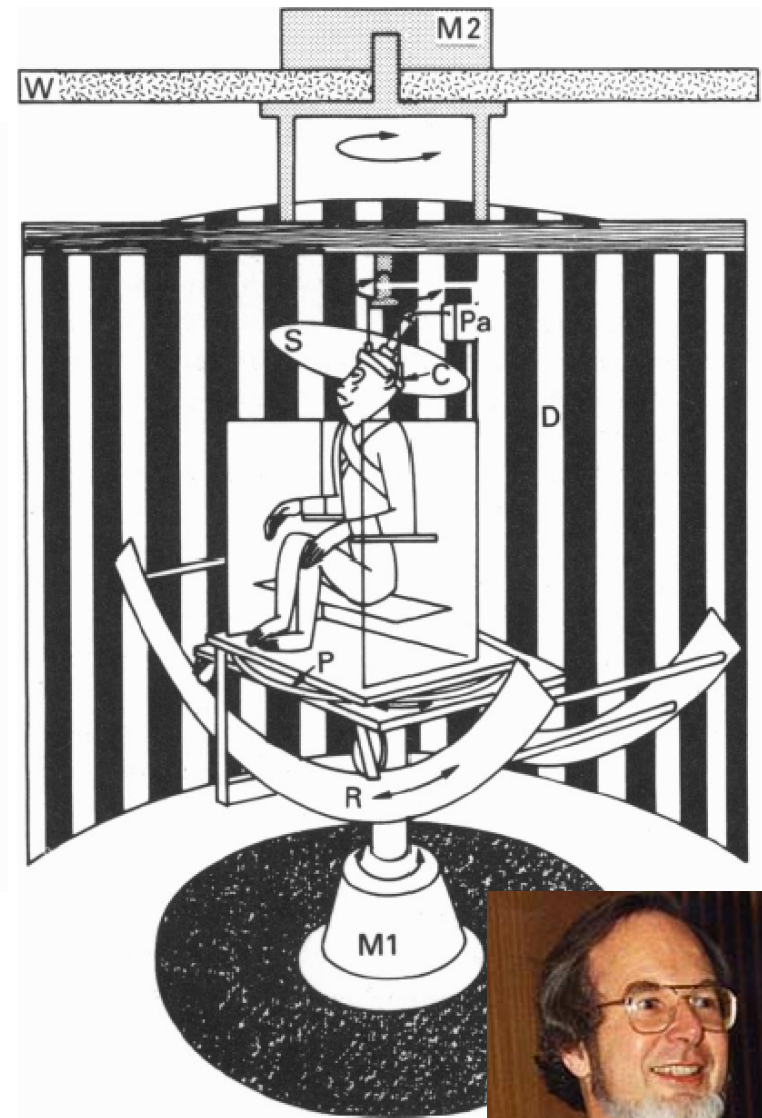
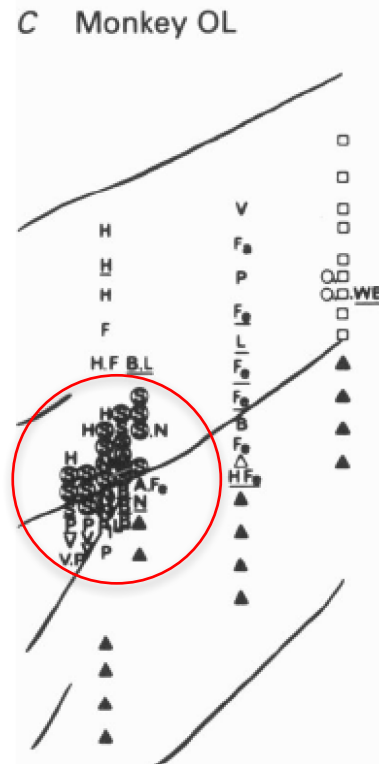
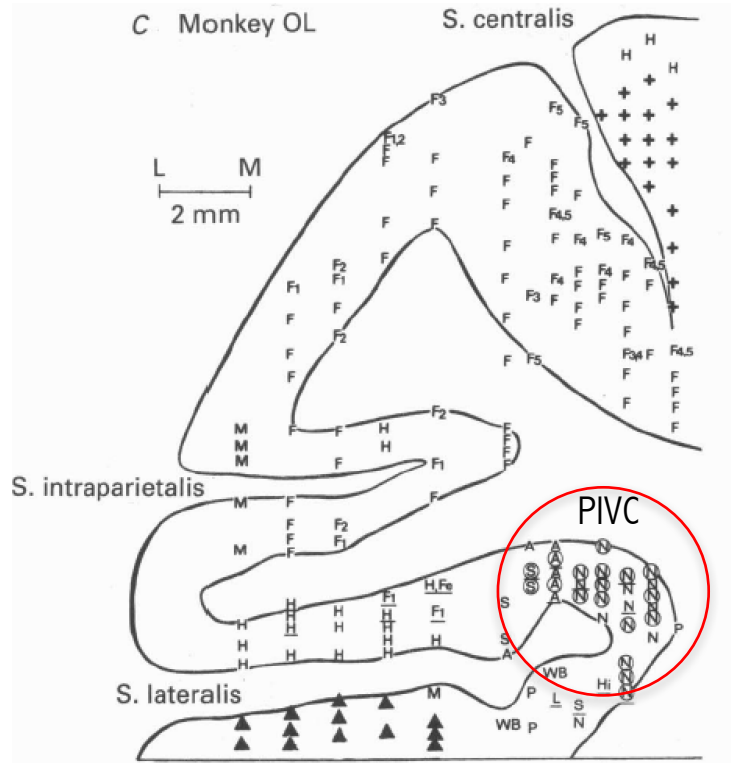


67J-20(I-8-32-10A) EQUILIBRIUM TEST SCHOOL OF AVIATION MEDICINE



# Prior electrophysiology on self-motion perception

Grüsser et al (1990)



## Somatosensory:

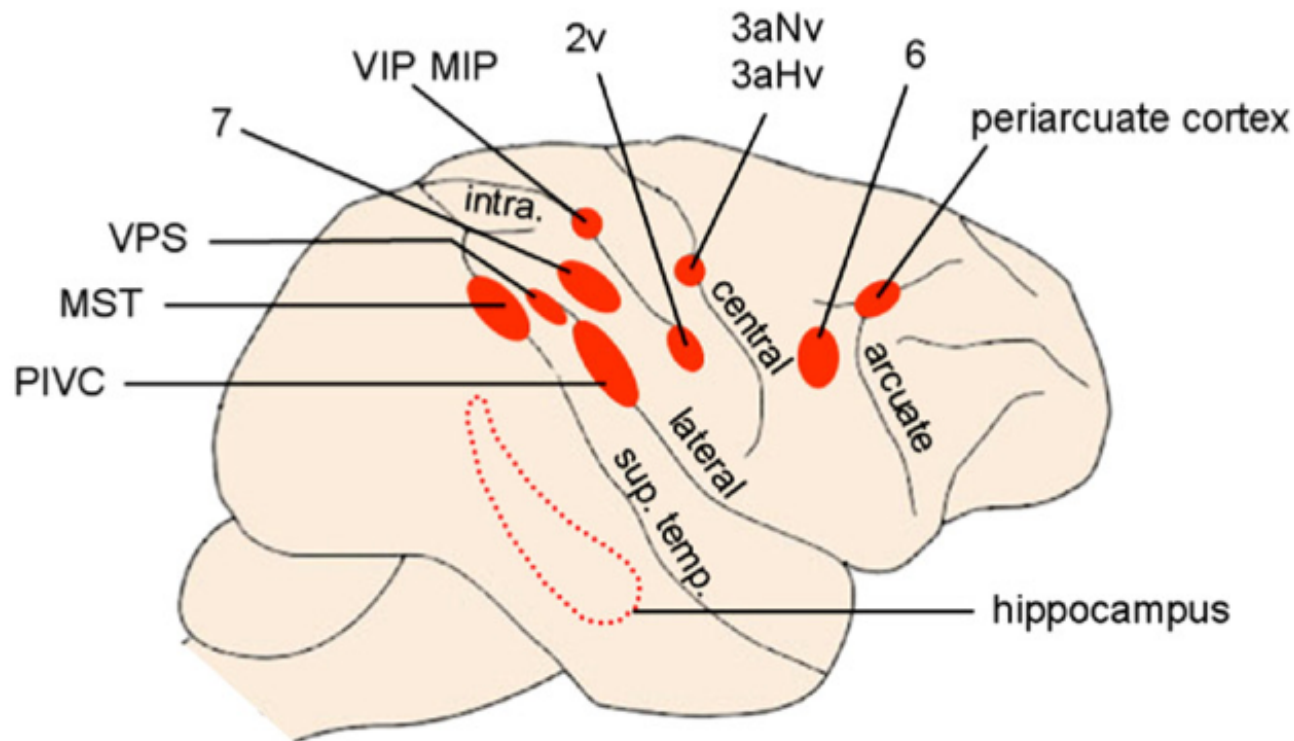
- |              |                               |                |
|--------------|-------------------------------|----------------|
| ○ Vestibular | A, arm                        | Hi, hip        |
| + Motor      | Fe, feet                      | L, leg         |
| ▲ Auditory   | F <sub>1-5</sub> , finger 1-5 | M, mouth       |
| □ Visual     | H, hand                       | N, neck        |
|              | H, contralateral              | P, pelvis      |
|              | <u>H</u> , bilateral          | S, shoulder    |
|              | C, chest                      | WB, whole body |
|              | Fa, face                      | T, tail        |
|              |                               | V, vertebra    |



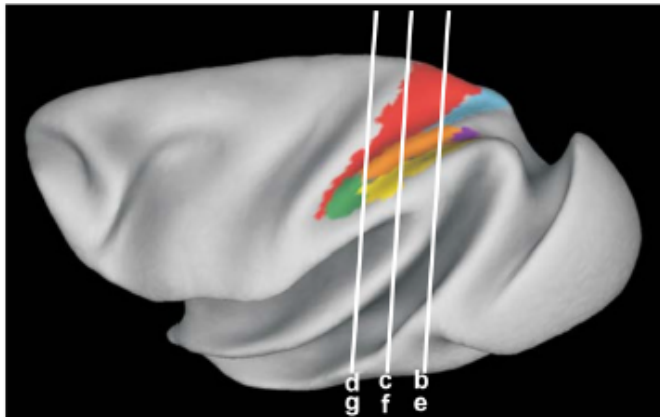
Otto-Joachim Grüsser (1932–1995)

# Prior electrophysiology on self-motion perception

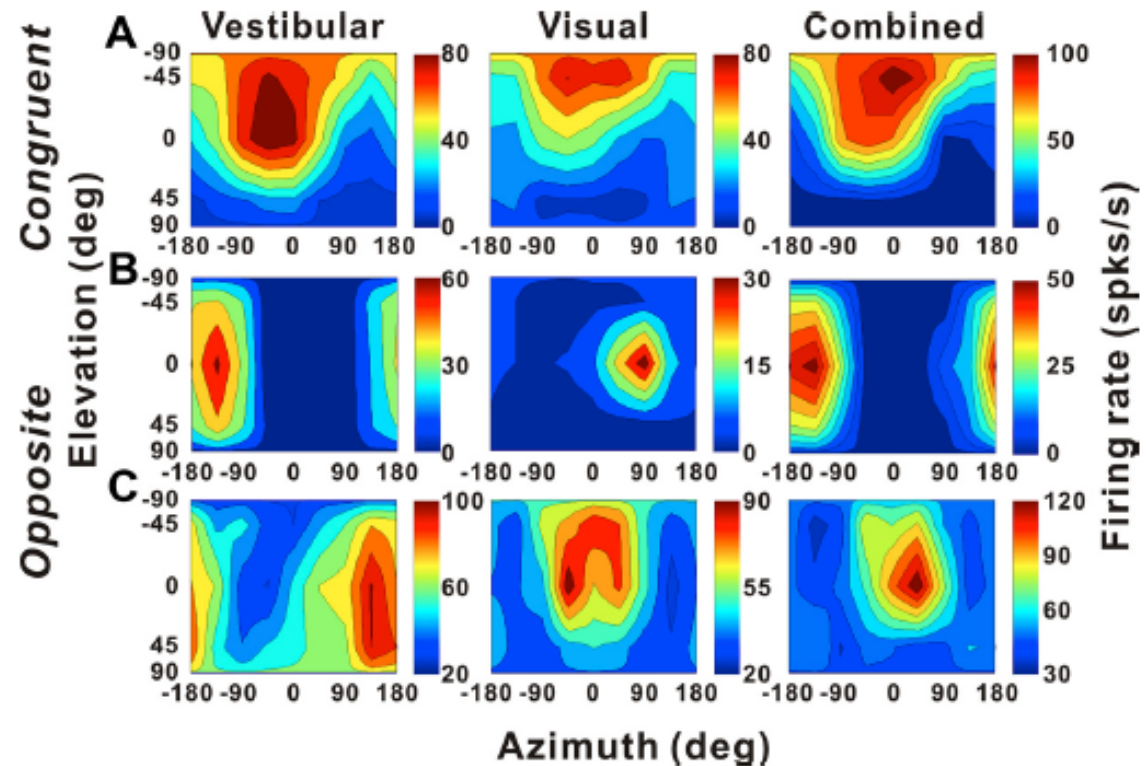
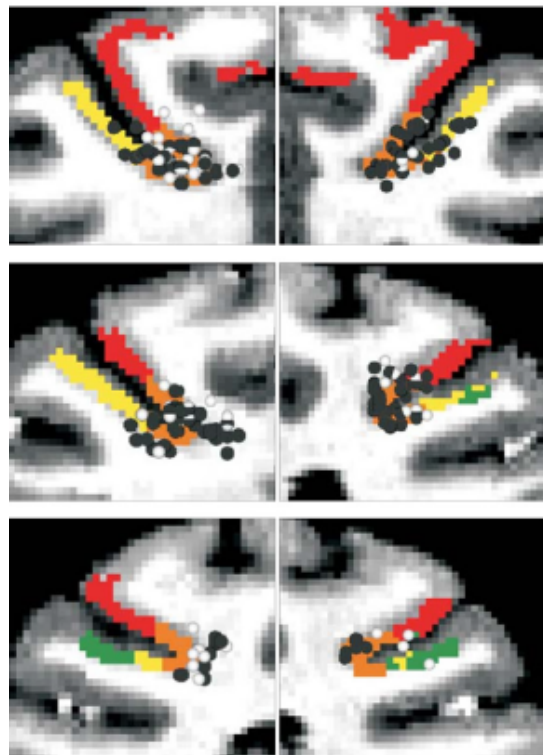
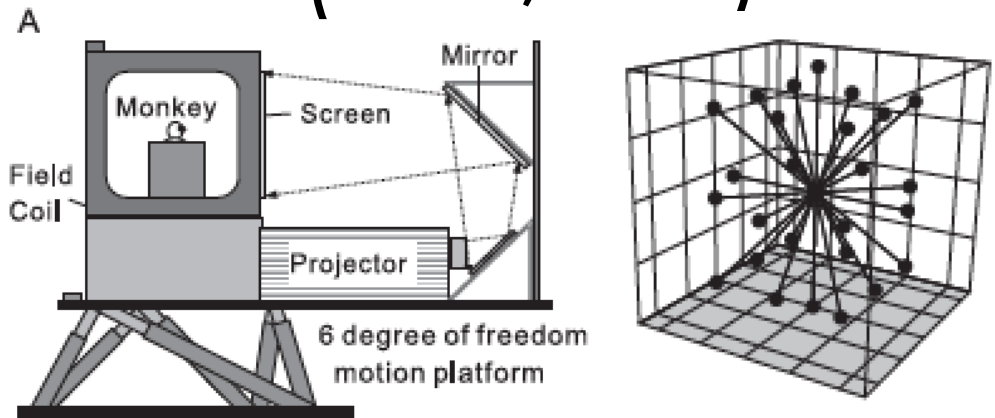
- research on the vestibular system
  - Guldin & Grüsser (1998), Chen et al (2011), Lopez & Blanke (2011) – primate studies
    - vestibular cortical system with several processing regions
    - PIVC / VPS / VIP / MST as core part of the vestibular network



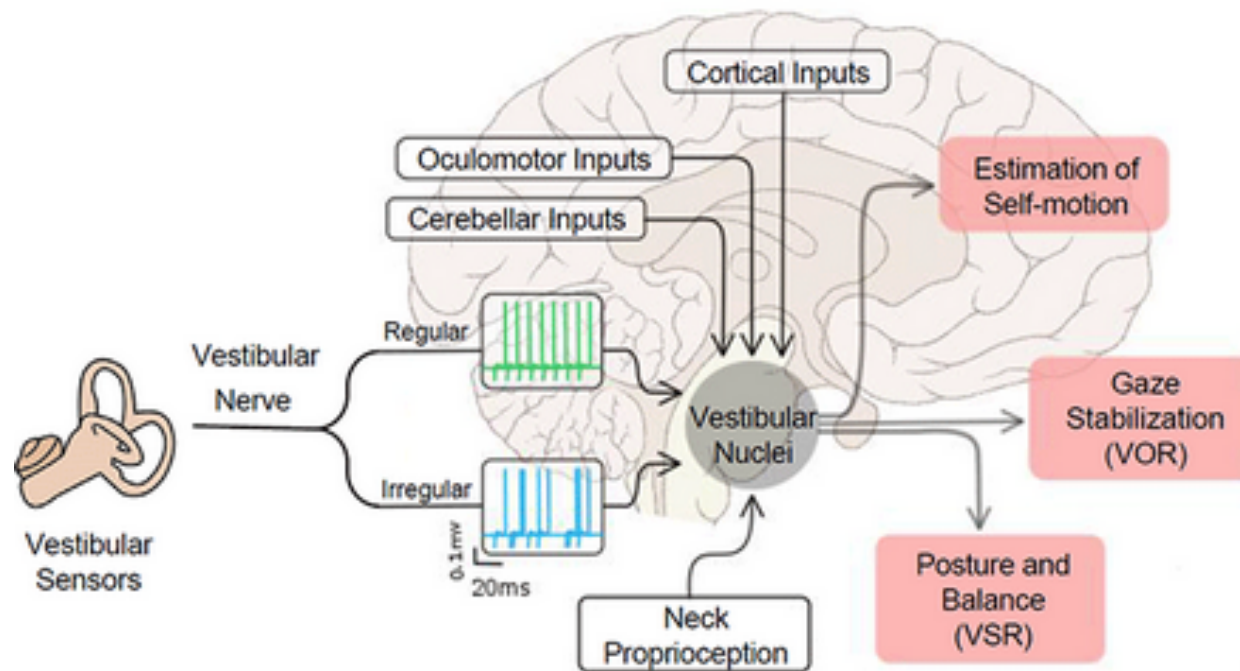
# Visual – vestibular interactions in visual posterior sylvian area (VPS, VIP)



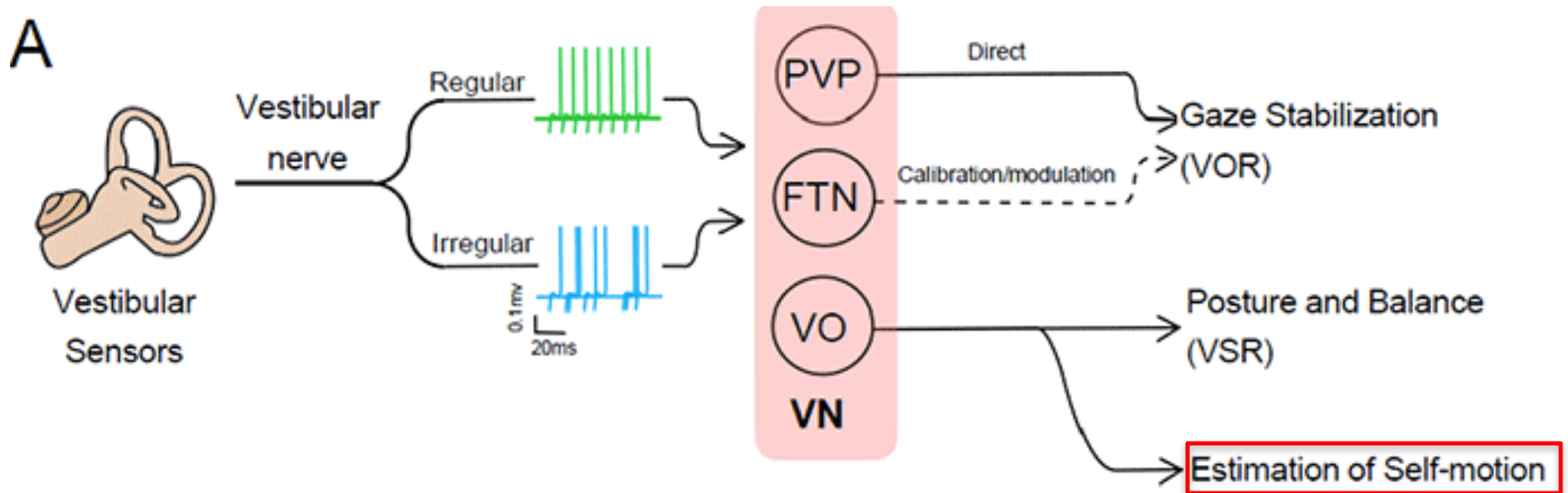
VIP  
LIP  
5  
MIP  
AIP



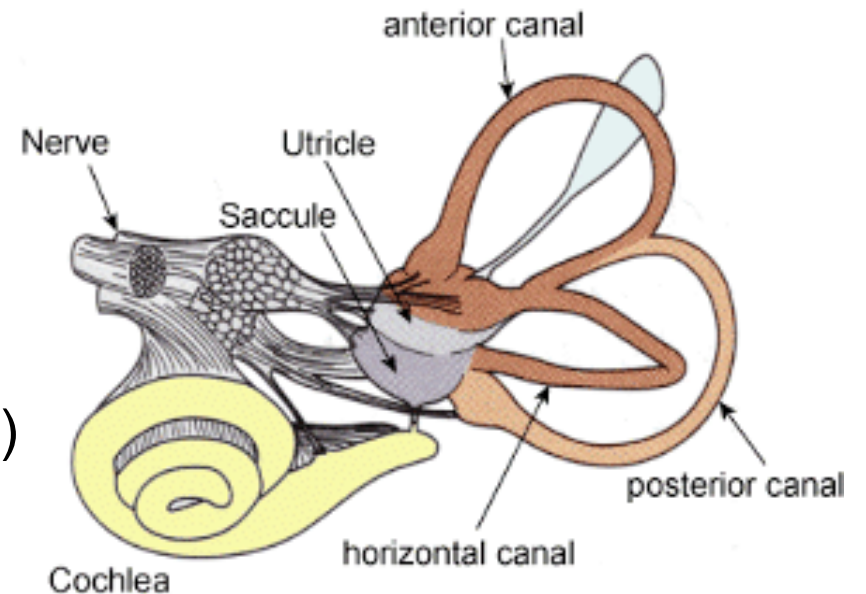
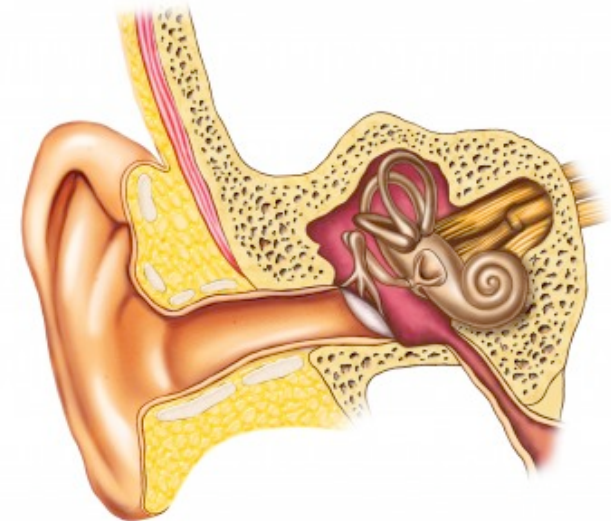
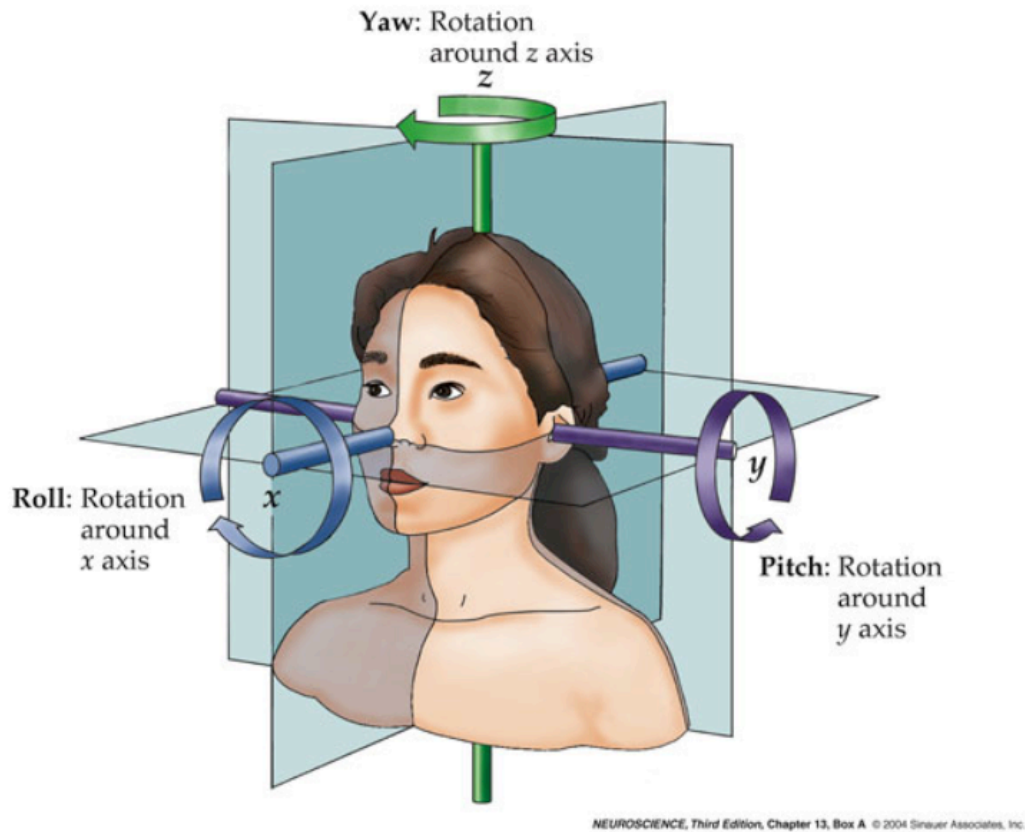
# Multisensory Convergence in Vestibular System



# Multisensory Convergence in Vestibular System



# Vestibular System

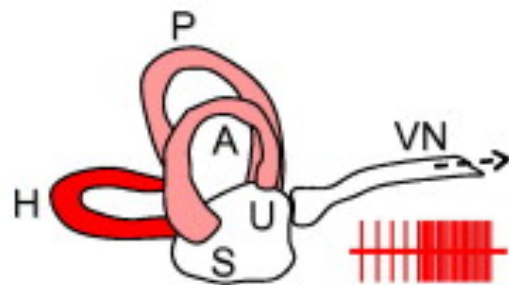


- Angular acceleration (semicircular canals)
- Linear acceleration (otoliths)

## A caloric vestibular stimulation (CVS)



Injection of cold (0,4,10,20°C) or warm (44°C) water or gas into the external auditory canal.

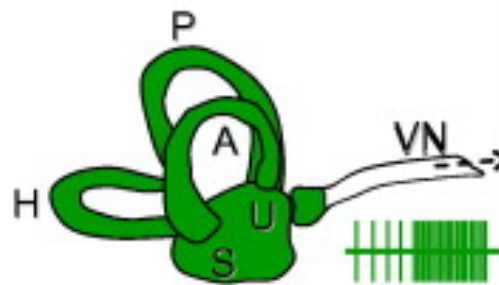


Warm water increases firing rate mainly in the afferents of the horizontal semicircular canals. A weaker contribution of vertical canals and an interaction with the neural processing of otolithic signals have been demonstrated.

## B galvanic vestibular stimulation (GVS)



Application of a percutaneous current through an anode and a cathode placed on the opposite mastoid processes.

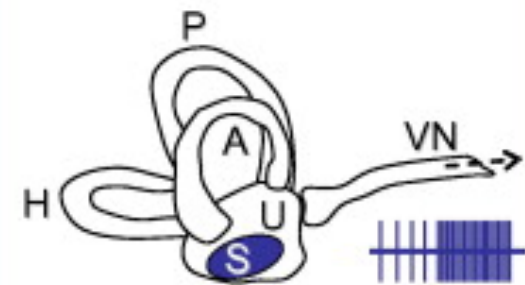


Firing rate increases in the vestibular afferents ipsilateral to the cathode and decreases to the side of the anode.

## C sound-induced vestibular stimulation



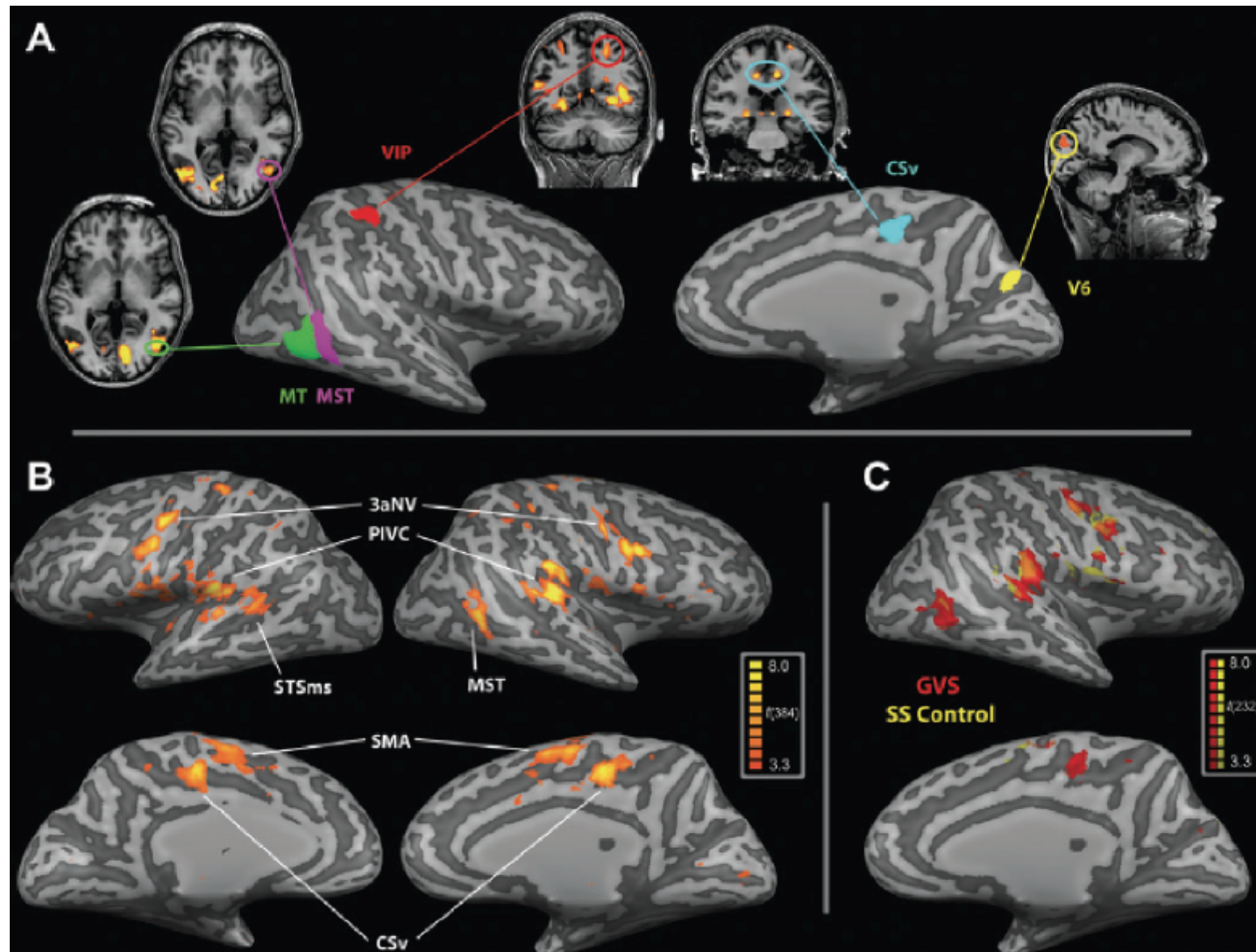
Presentation of 102 dB clicks (1 ms long, at 1 Hz) or short tone bursts (10 ms long, 500 Hz, at 3 Hz) through headphones.



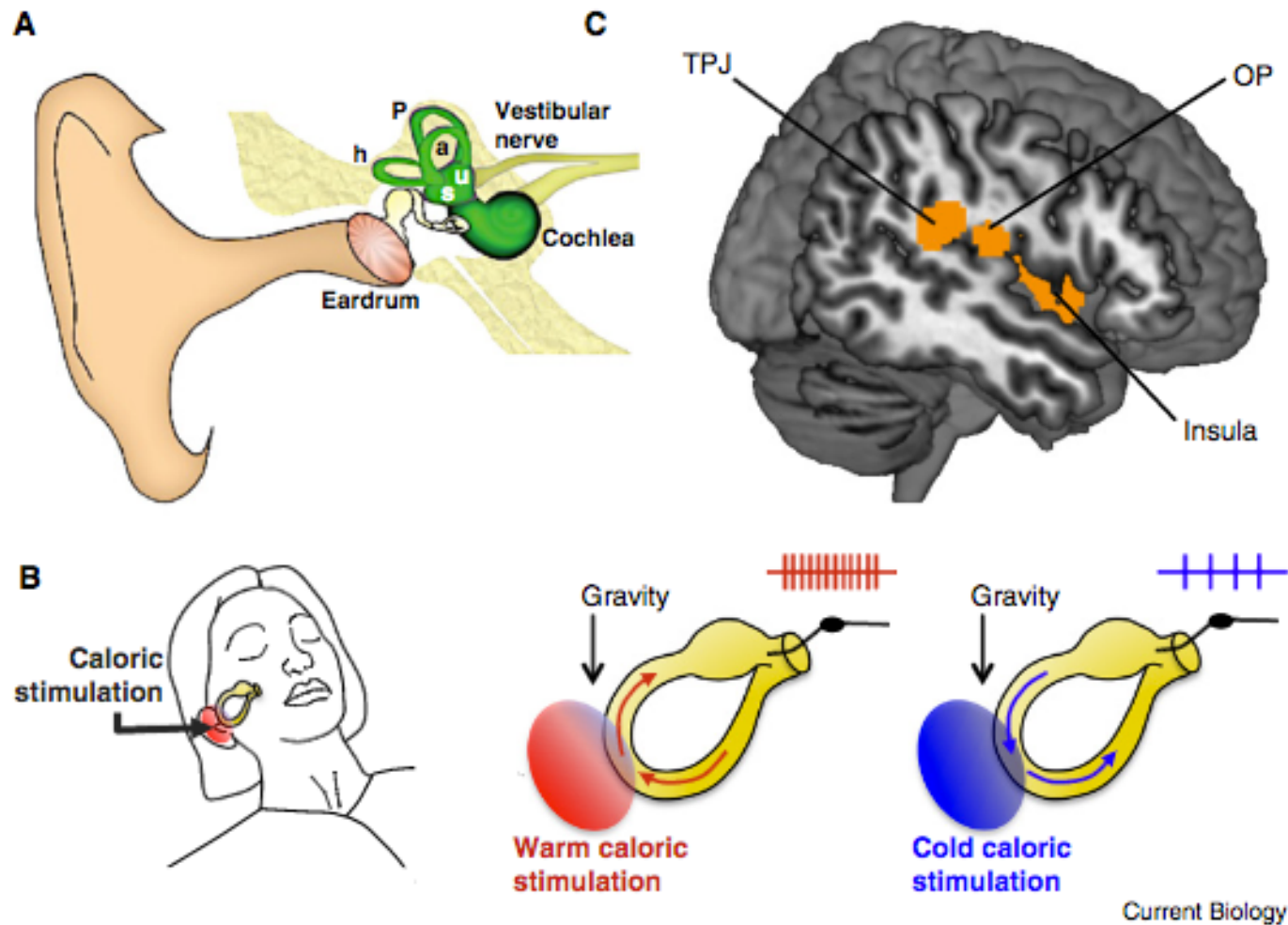
Air-conducted sounds preferentially activate saccular receptors. A weaker contribution of other otolithic receptors and semicircular canals has also been proposed.



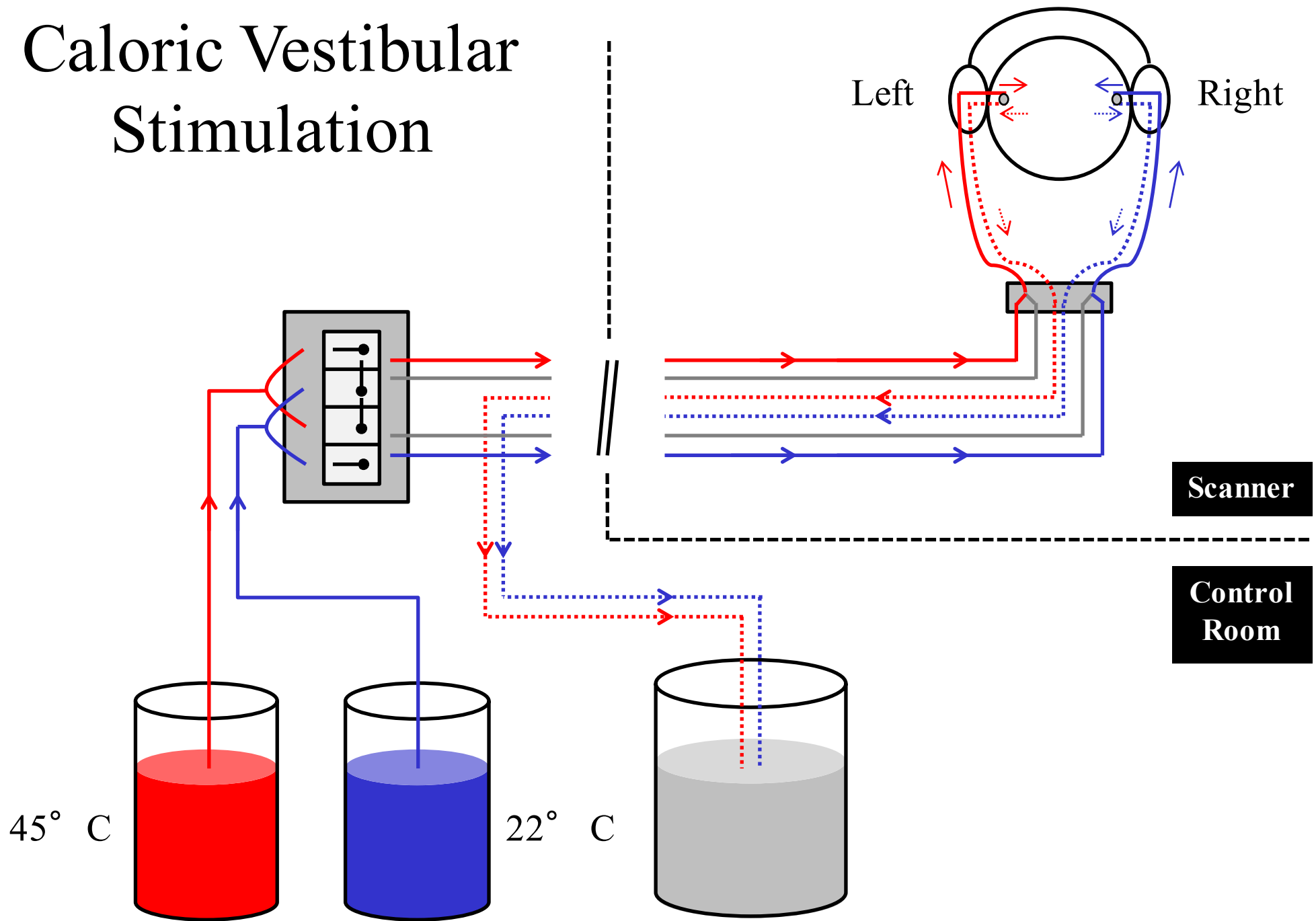
# fMRI during Galvanic Vestibular Stimulation

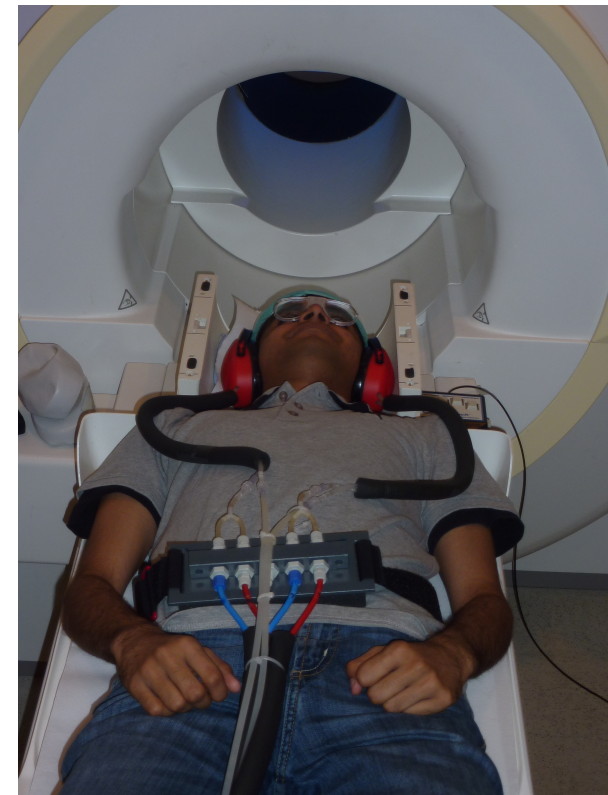


# Caloric Vestibular Stimulation

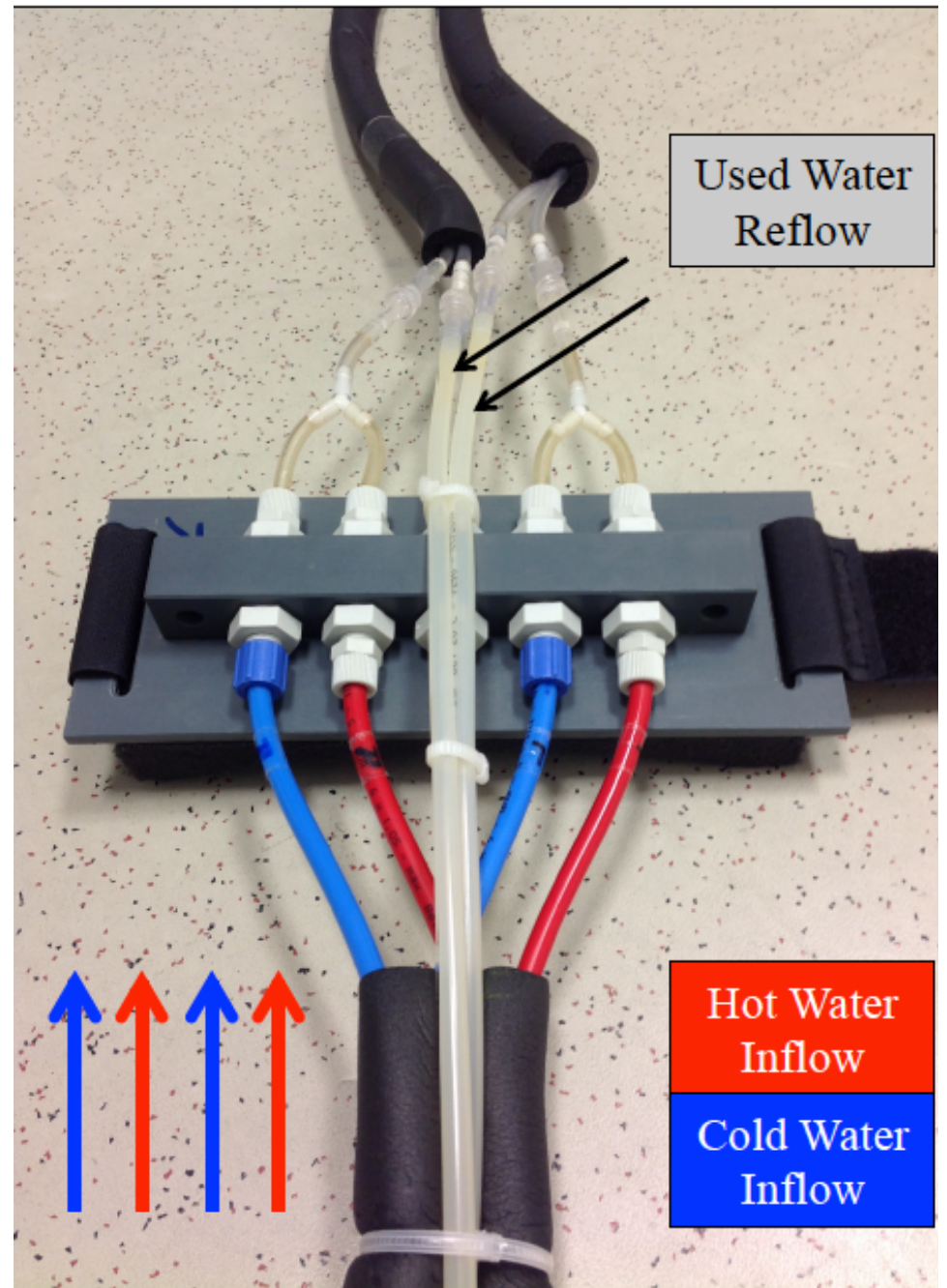
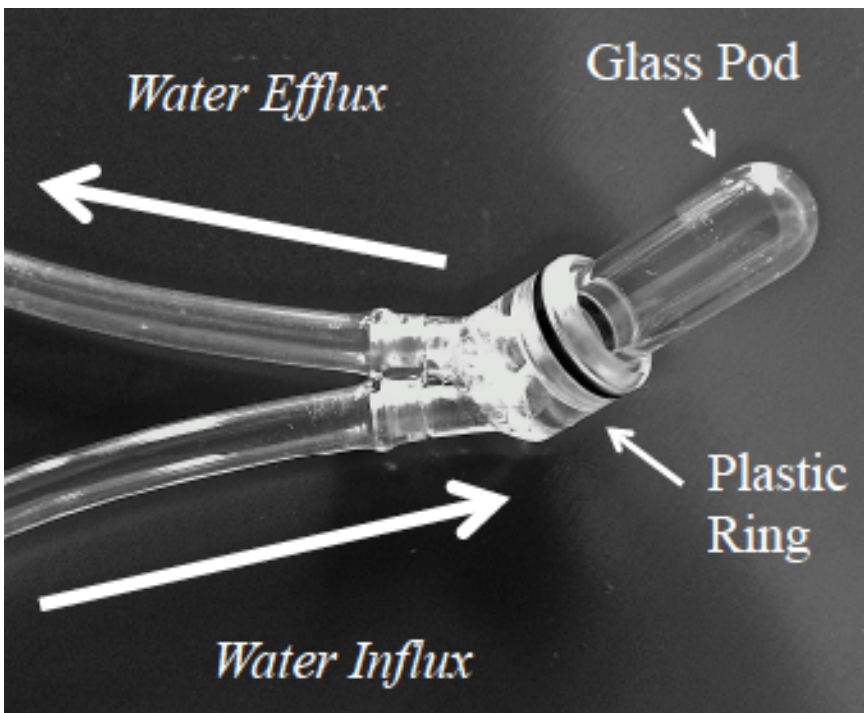
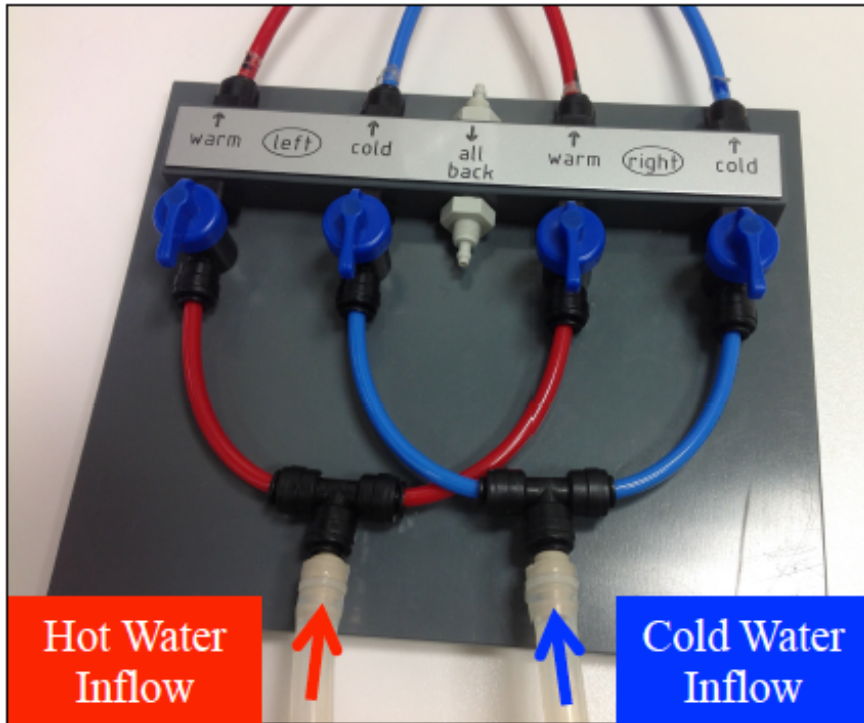


# Caloric Vestibular Stimulation

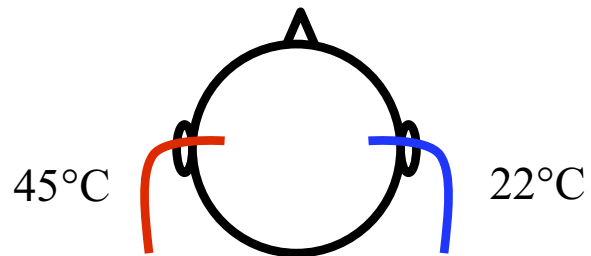




Frank & Greenlee, 2014 J Neuroscience Methods

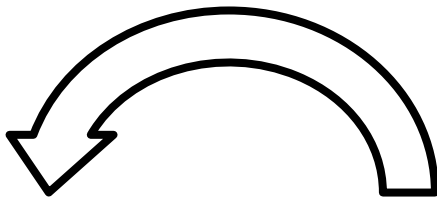


# Caloric Conditions

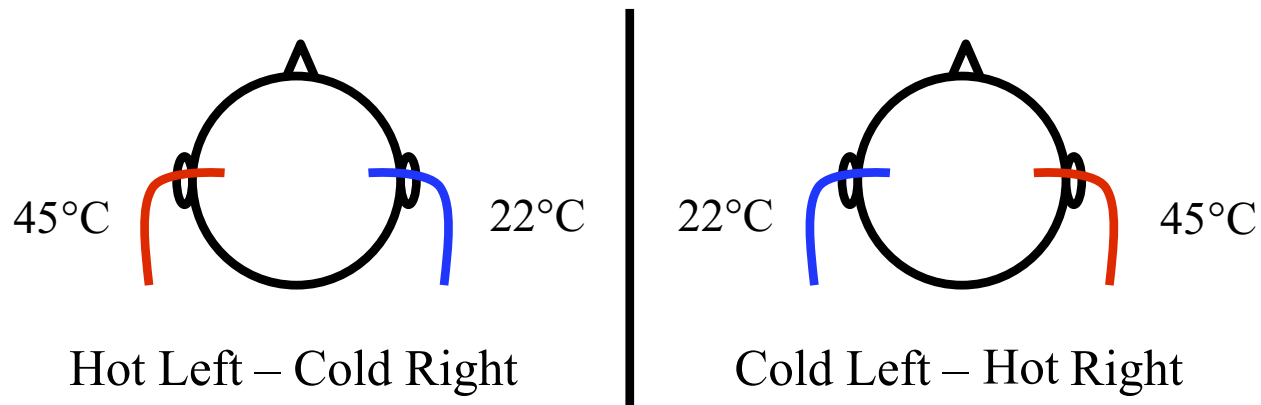


Hot Left – Cold Right

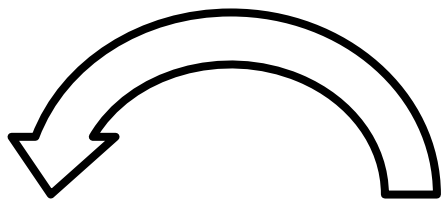
Rotation to left



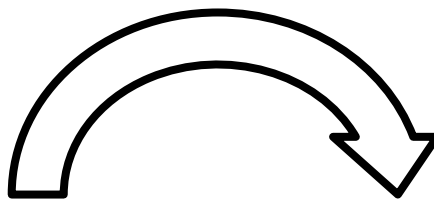
# Caloric Conditions



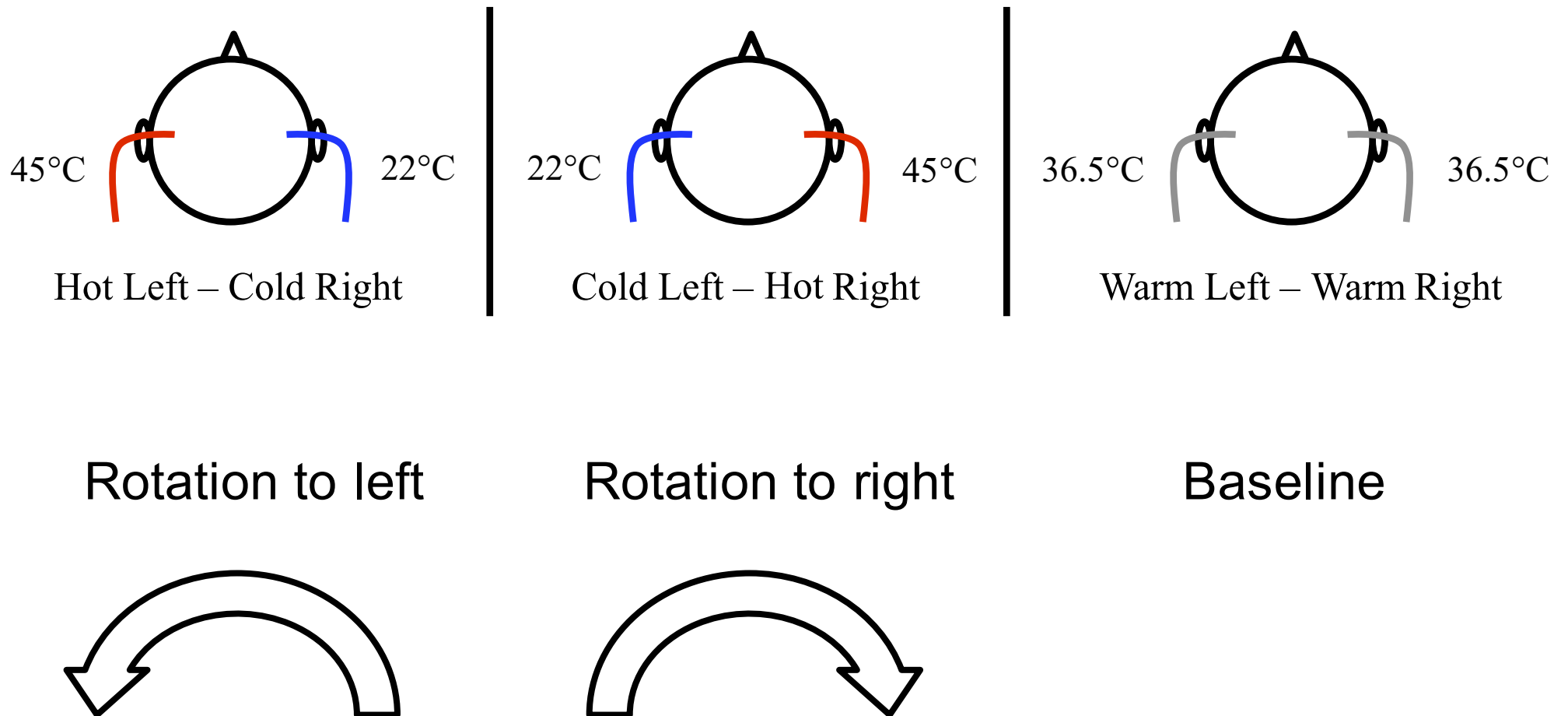
Rotation to left



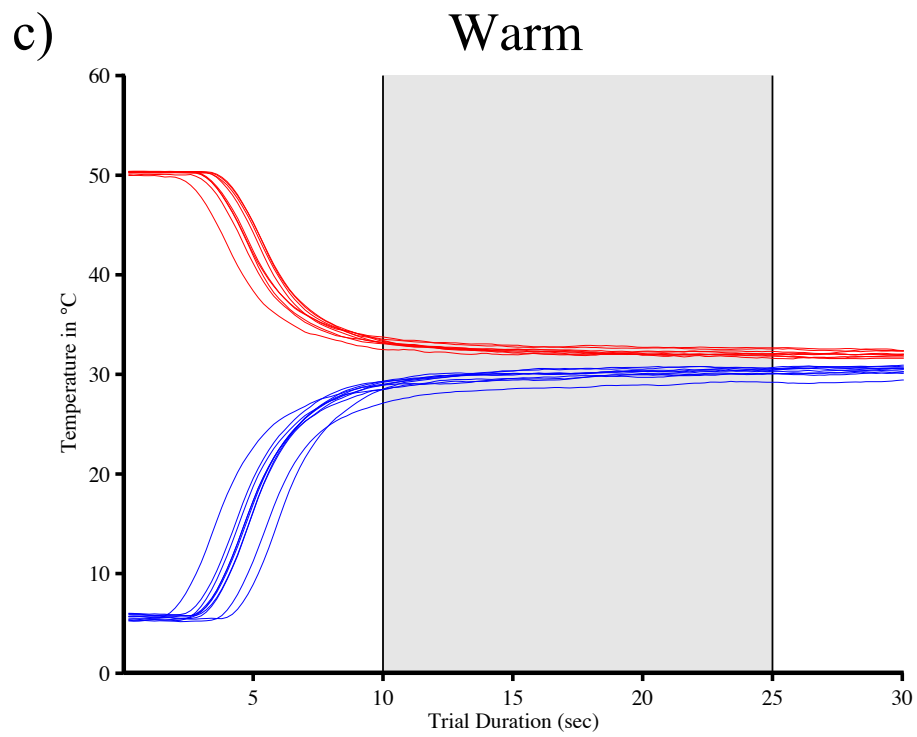
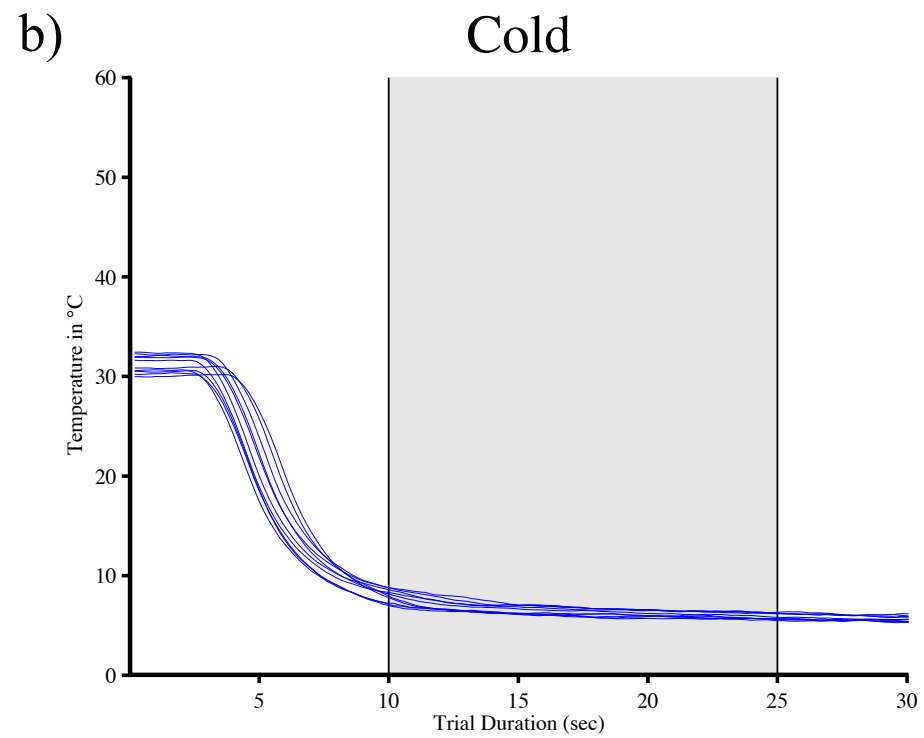
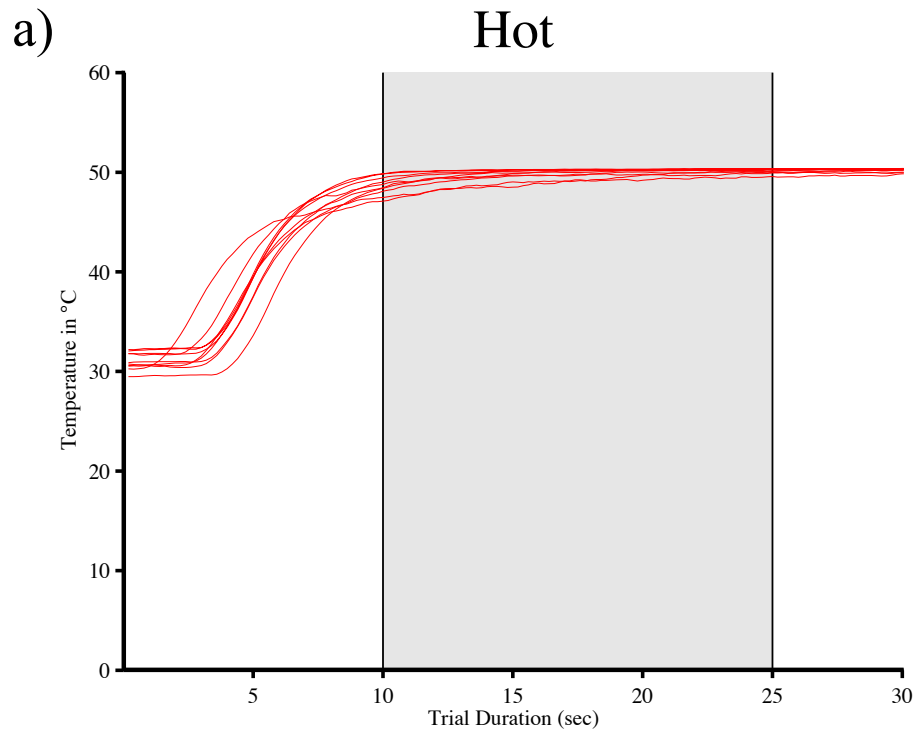
Rotation to right



# Caloric Conditions







# Water Circulation vs. No Circulation



$p < 1.0000e-10$

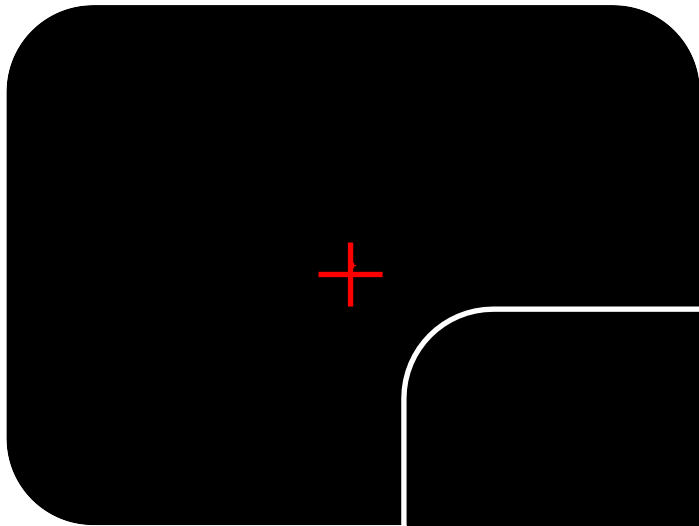


$p < 1.0000e-10$

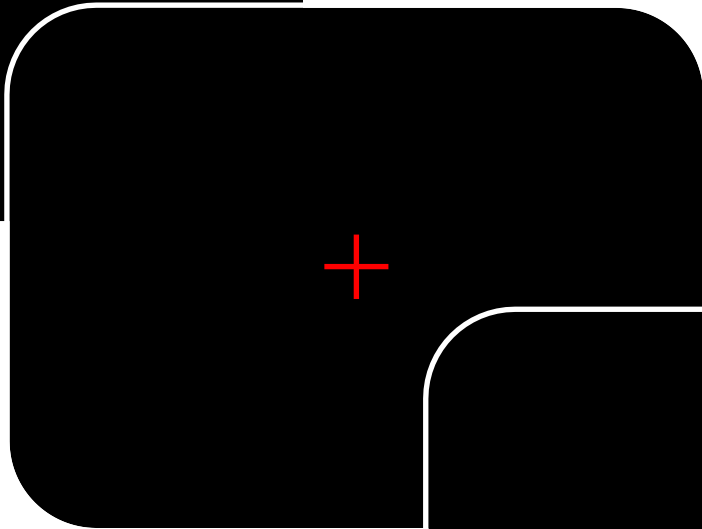
$p < 0.001$  (FDR-corrected)

0.5 – 1 sec

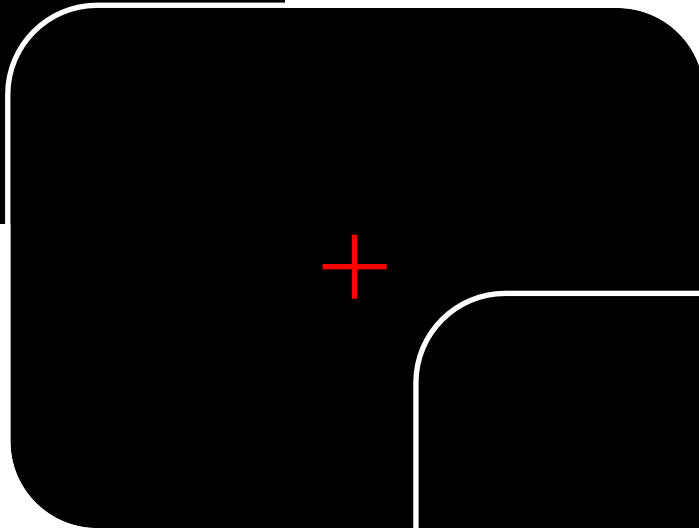
Vestibular



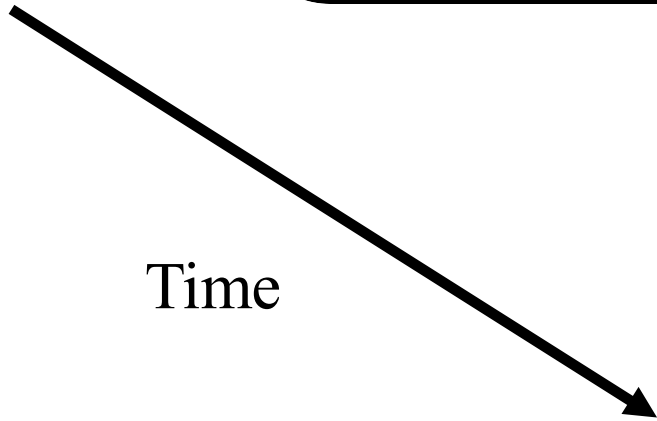
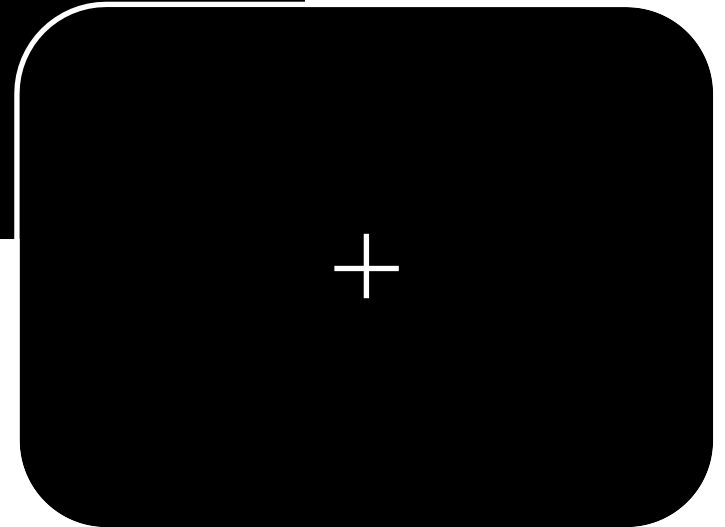
10 sec



15 sec



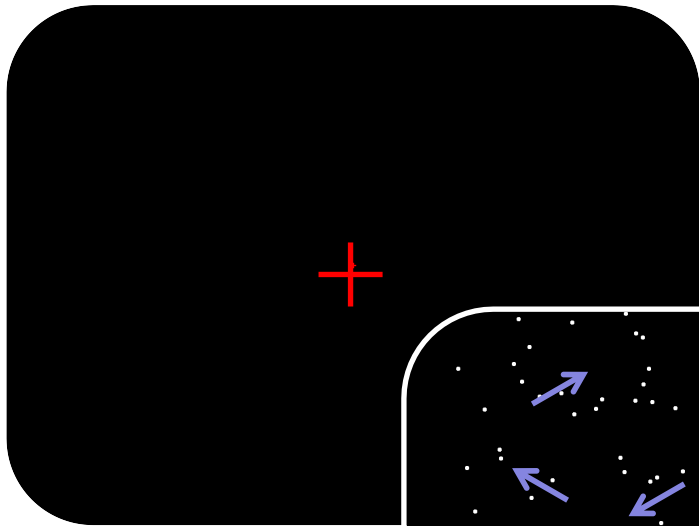
5 sec



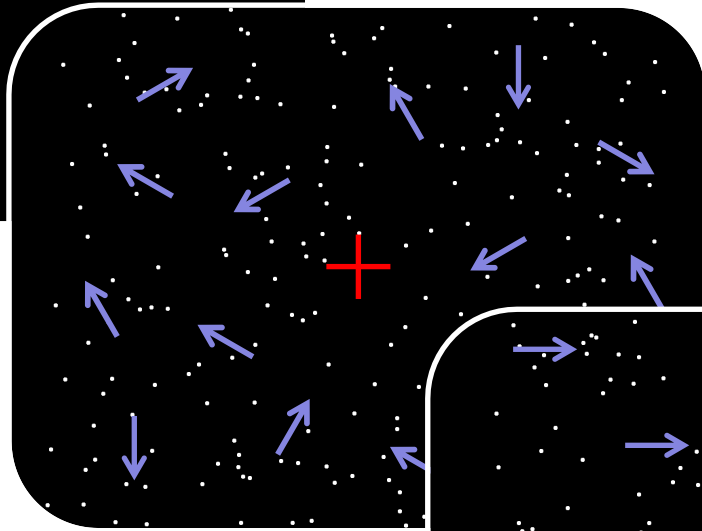
Time

# Visual-Vestibular

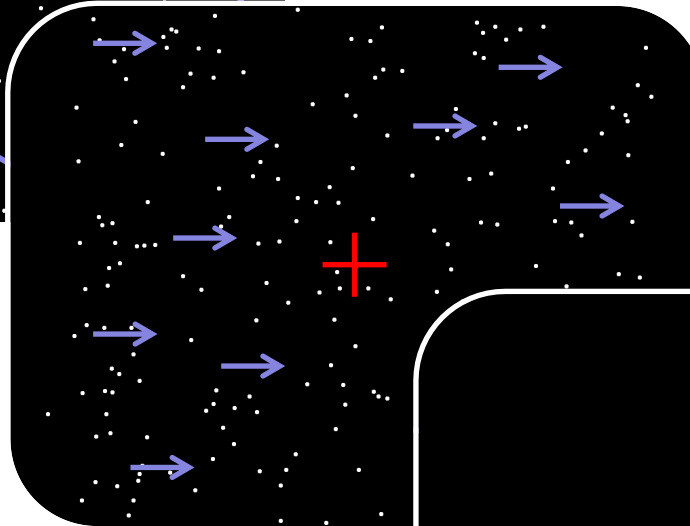
0.5 – 1 sec



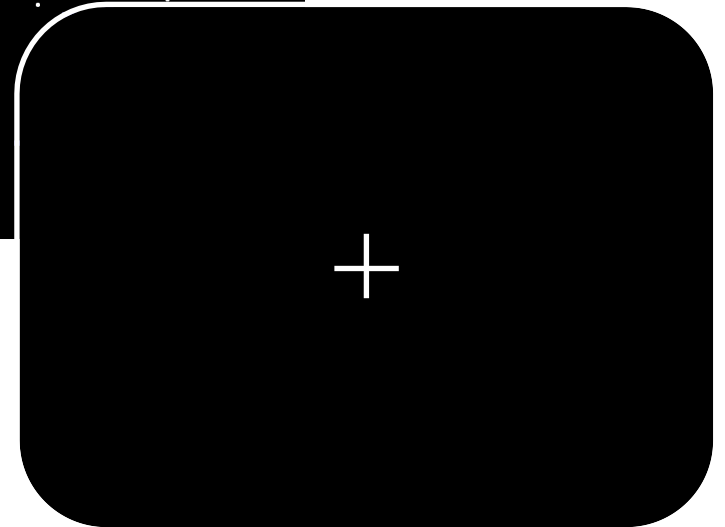
10 sec



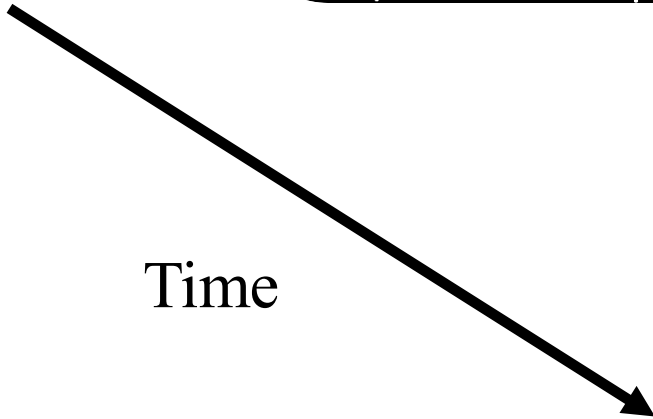
15 sec

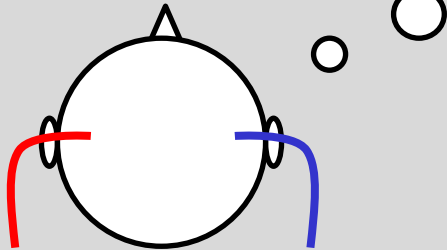
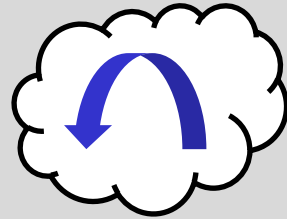
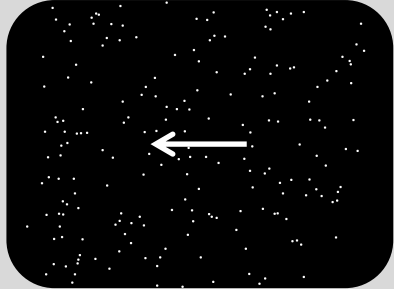


5 sec

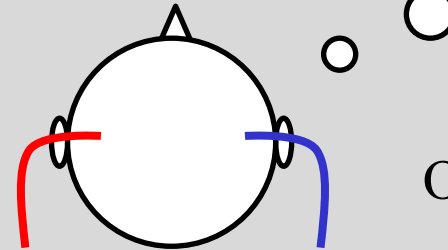
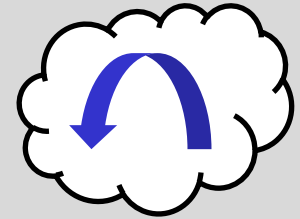
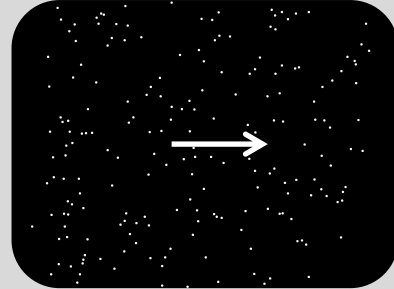


Time

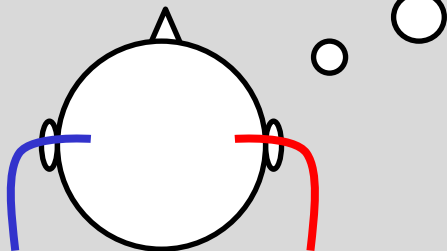
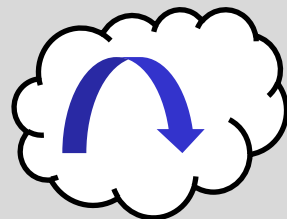
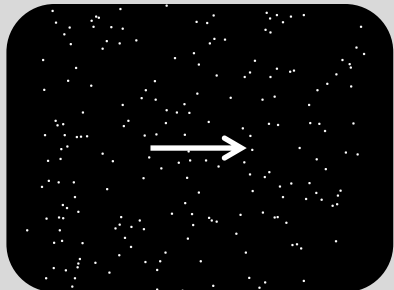




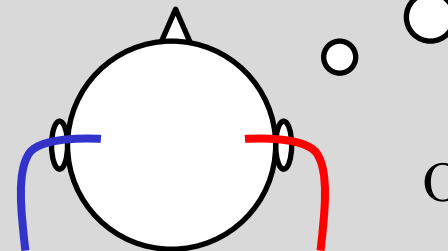
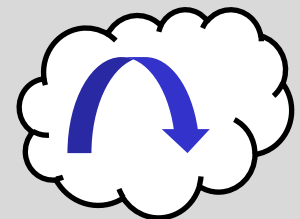
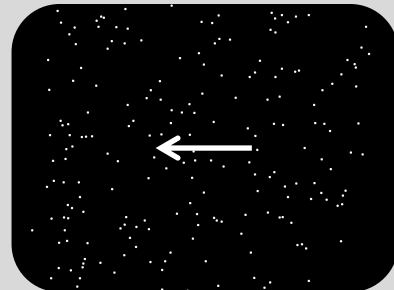
In-Phase



Out-of-Phase

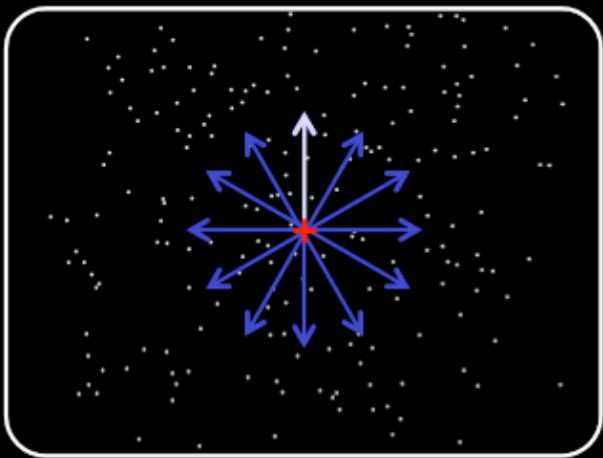


In-Phase

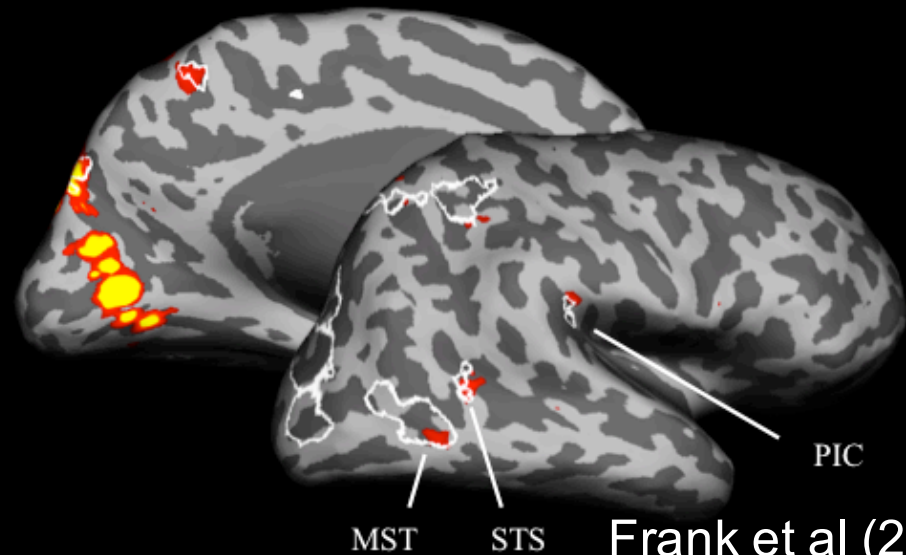
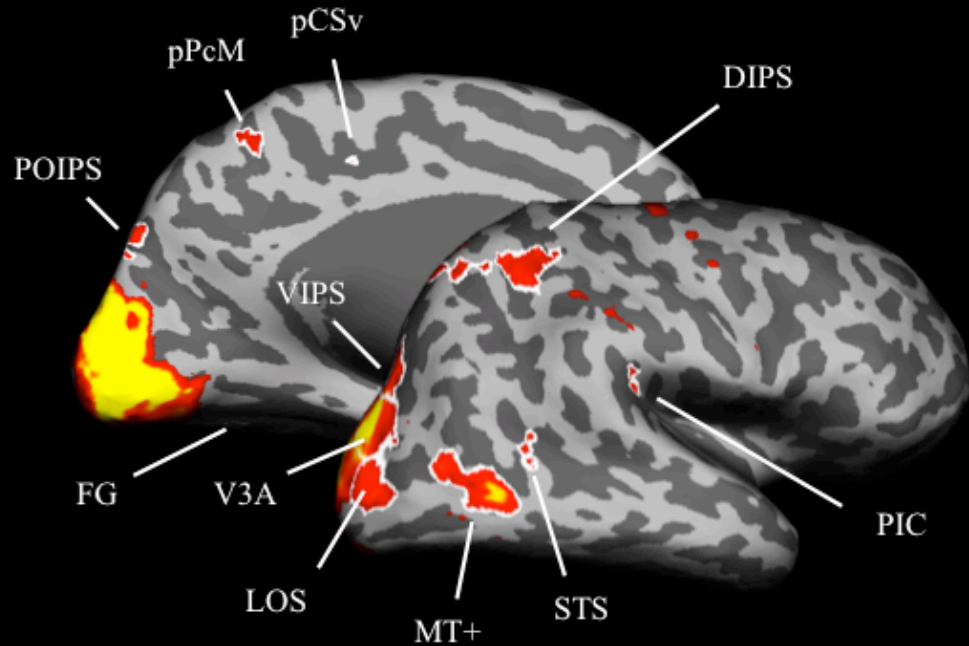
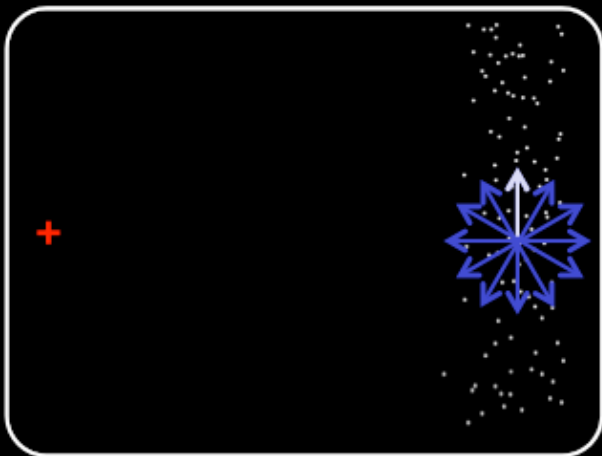


Out-of-Phase

# Whole Screen Visual Motion



# Peripheral Visual Motion

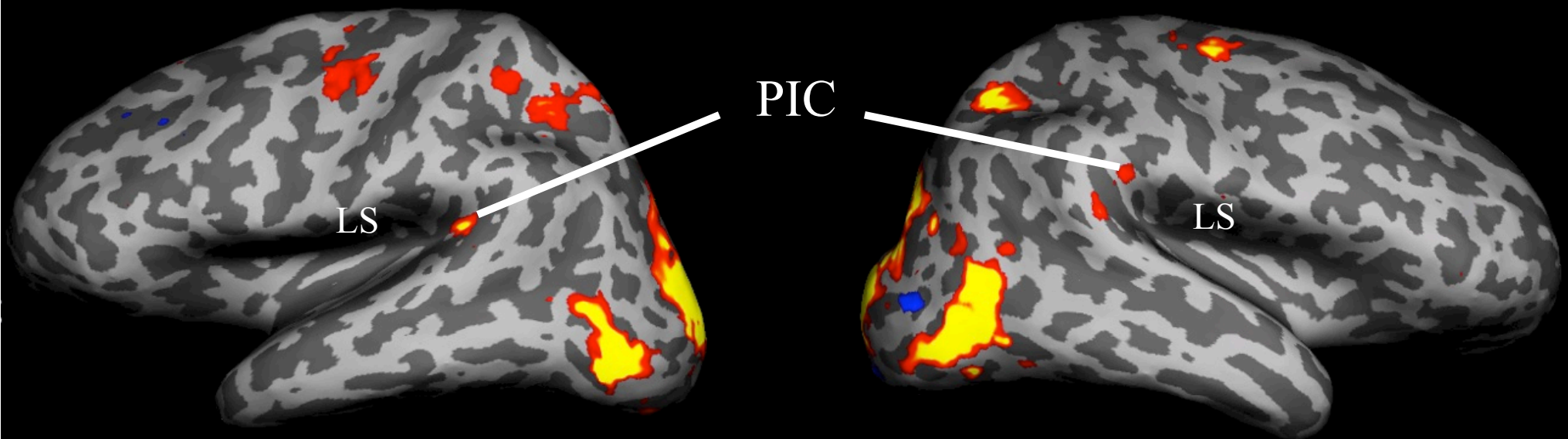


*Visual Motion Localizer*

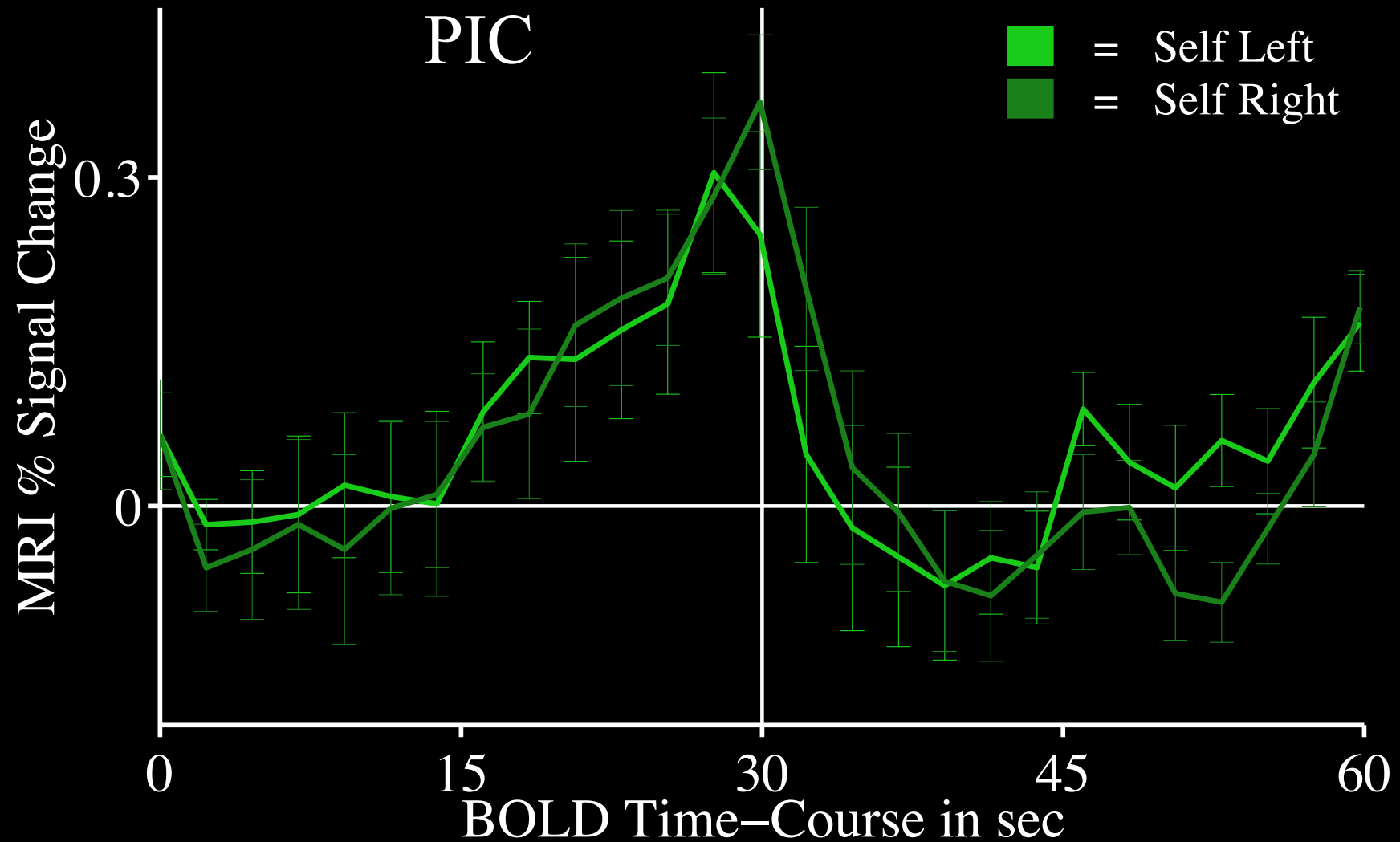
Frank et al (2014)

# Area PIC in Visual Motion

a) Visual Motion vs. Static

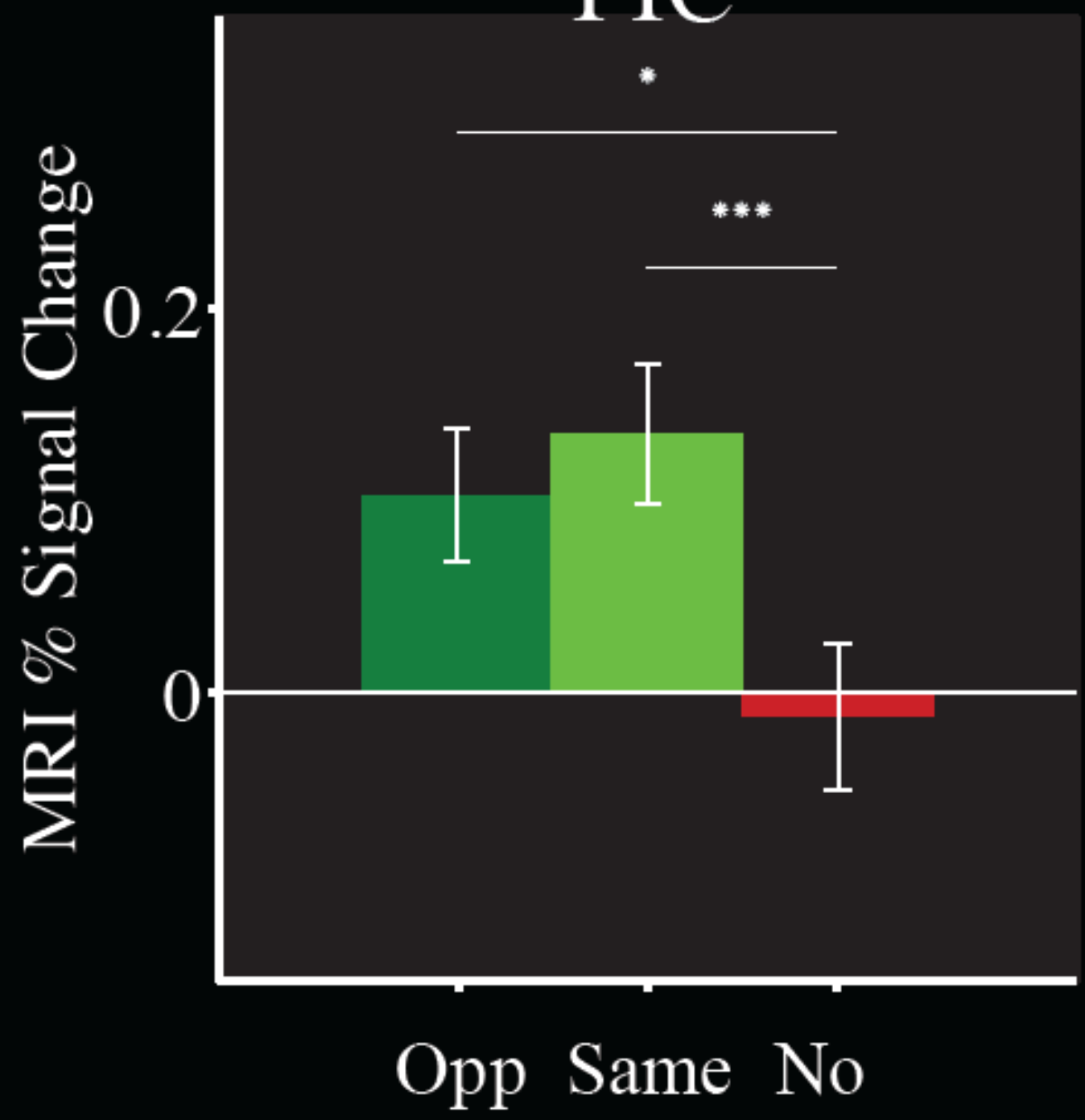


# d) Time-Course of Vestibular Response

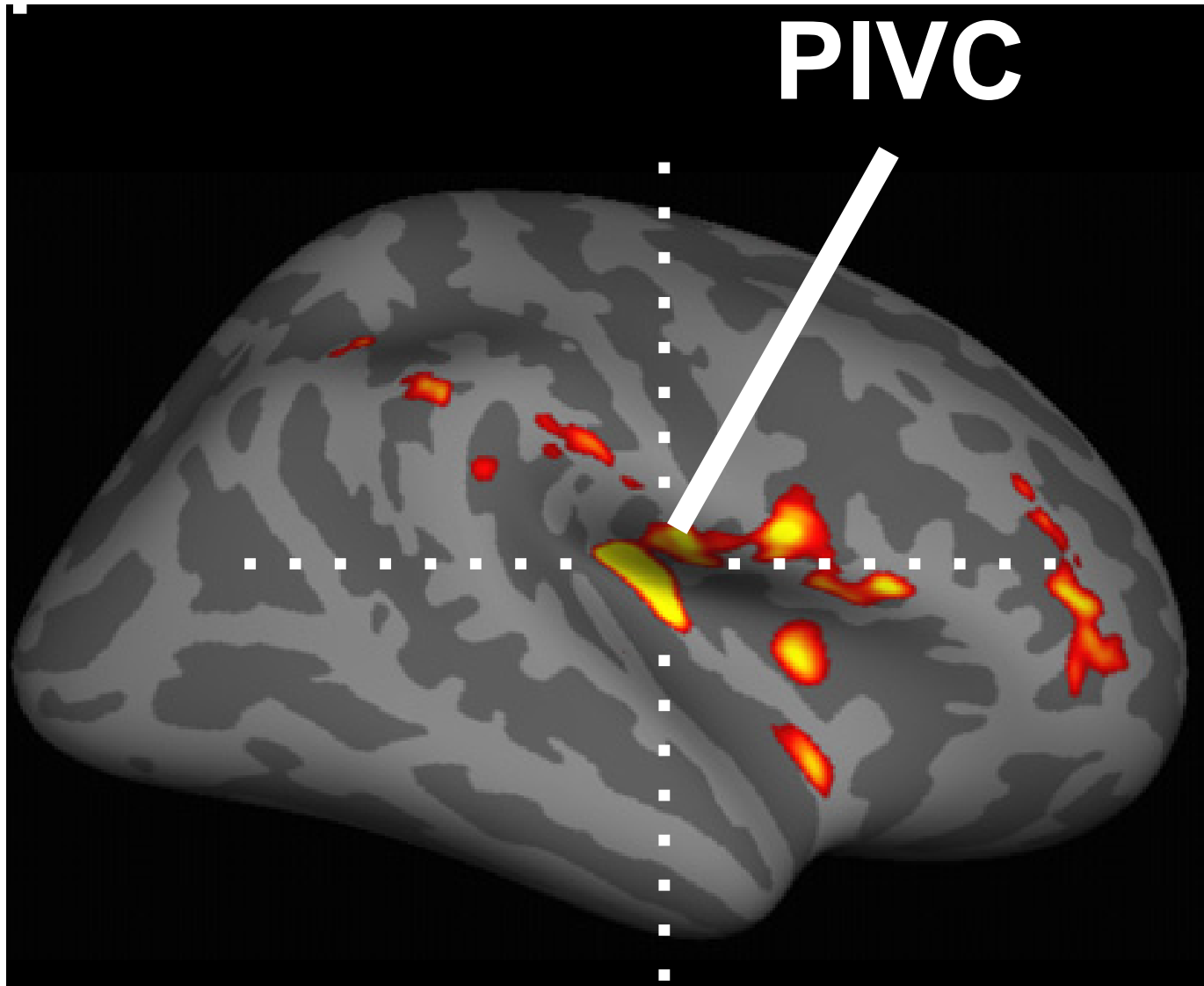




# PIC



# fMRI Contrast: Caloric > Baseline



N = 25  
subjects

# Research Issues

1. Inhibition of the vestibular system by visual attention
2. Biochemical effects of inhibition by visual attention

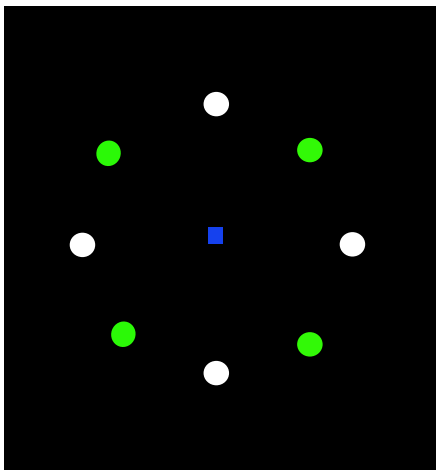
# Previous Results

- Cross-modal (visual/vestibular) influences activity in the vestibular cortex
  - Brandt, Bartenstein, Janek, Dieterich (1998)
  - Kleinschmidt, Thilo, Büchel, Gresty, Bronstein, Frackowiak (2002)
  - Seemungal, Guzman-Lopez, Arshad, Schultz, Walsh, Yousif (2013)
  - Frank, Baumann, Mattingley, Greenlee (2014)

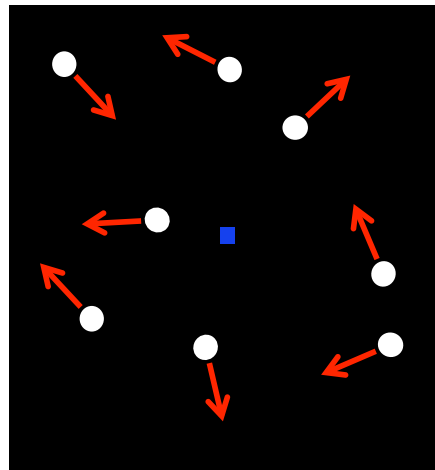
# Attentional Tracking Task

- Pylyshyn & Storm (1988)

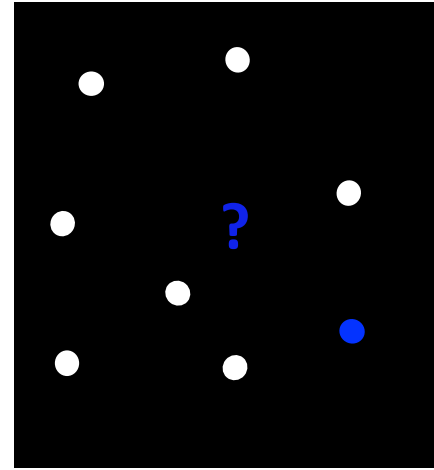
Cueing (2 s)



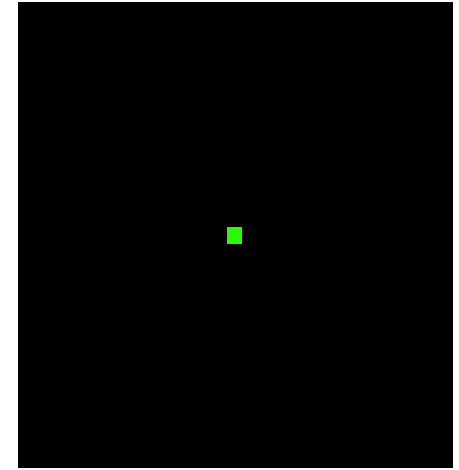
Tracking (14 s)

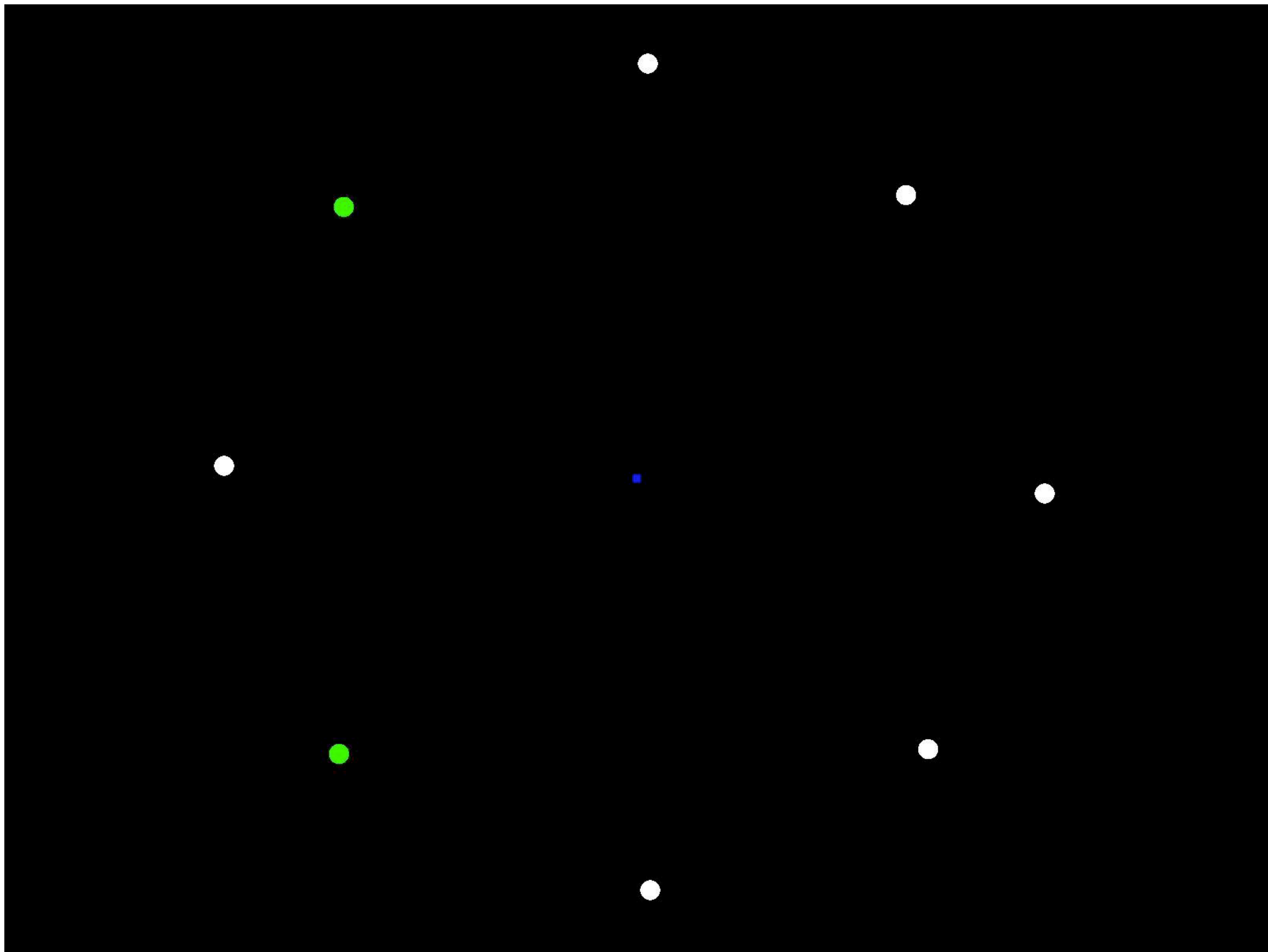


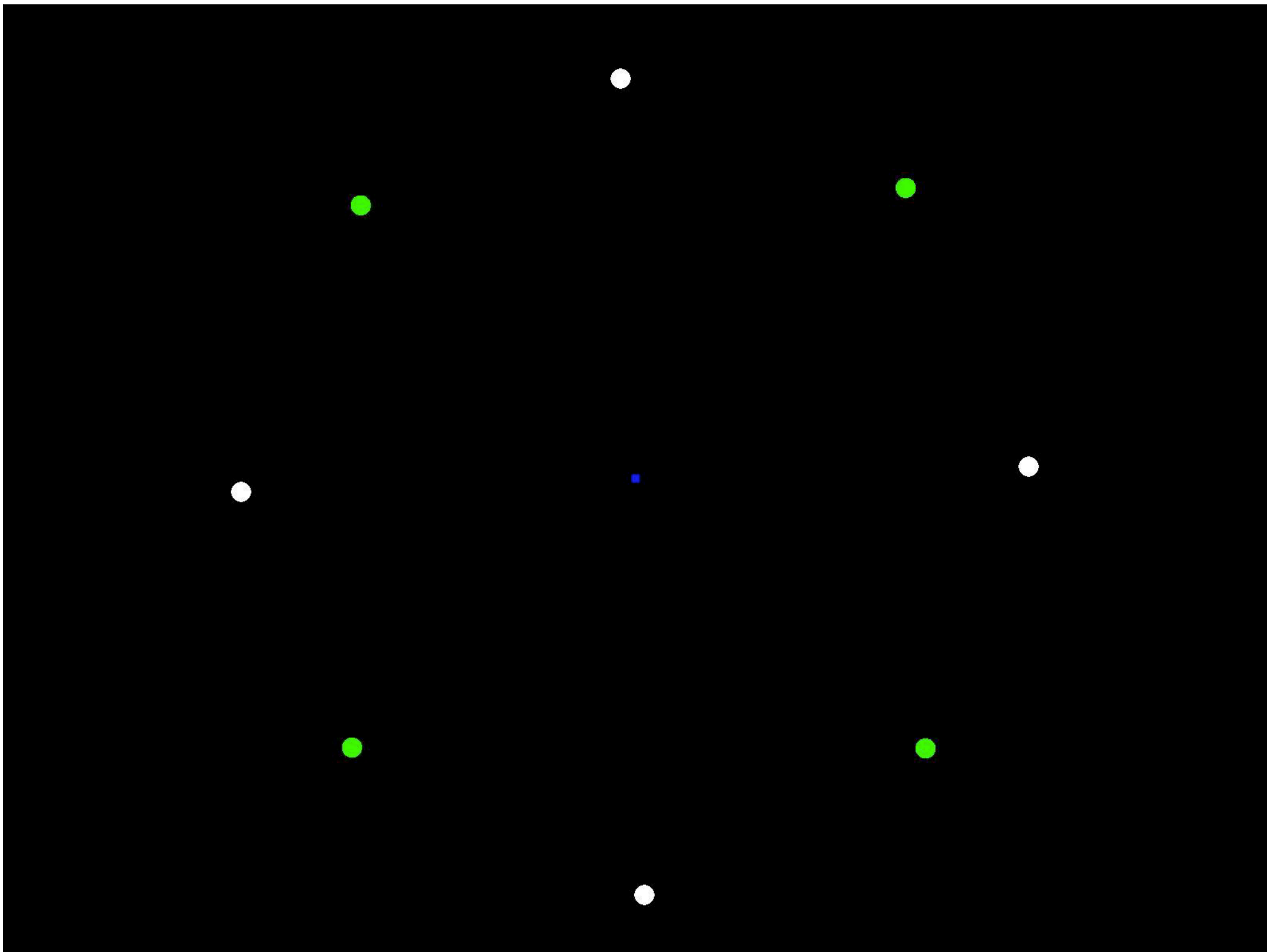
Response (2 s)



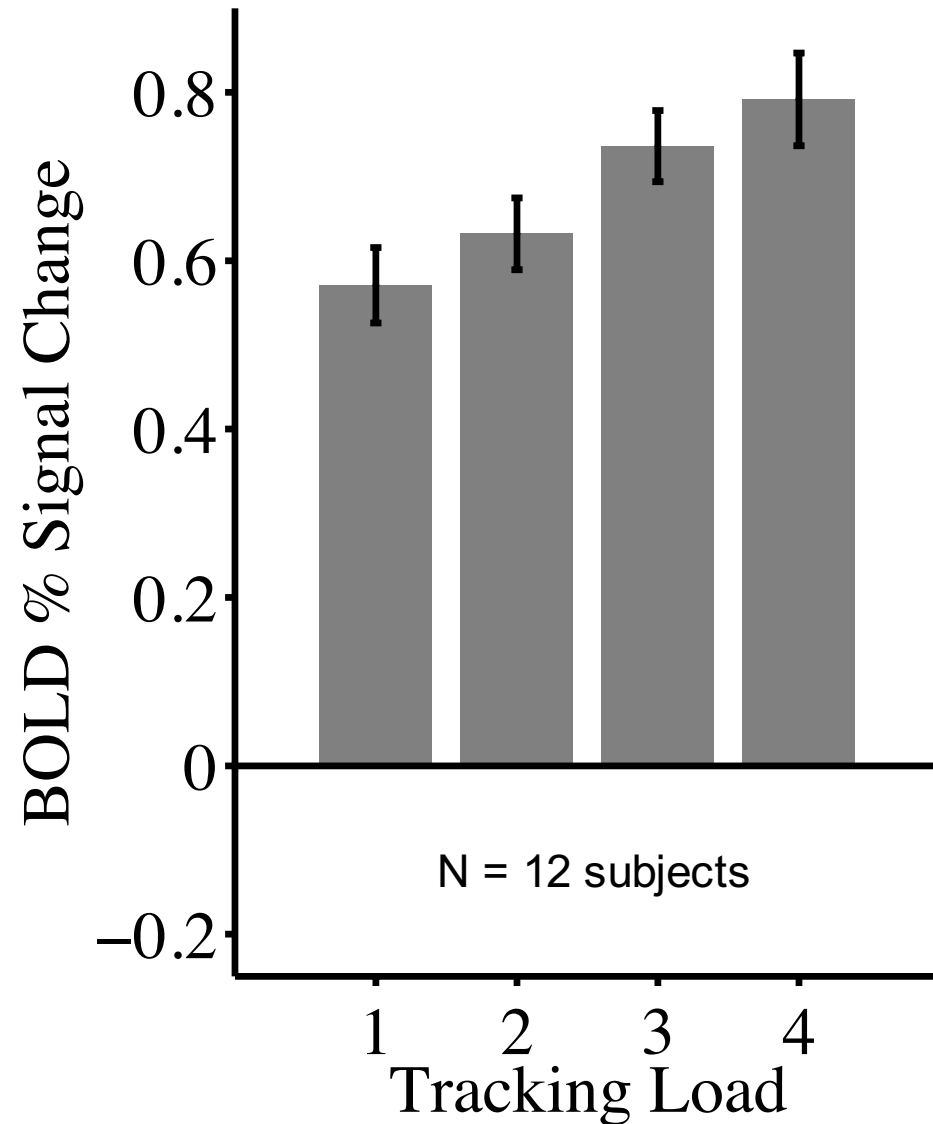
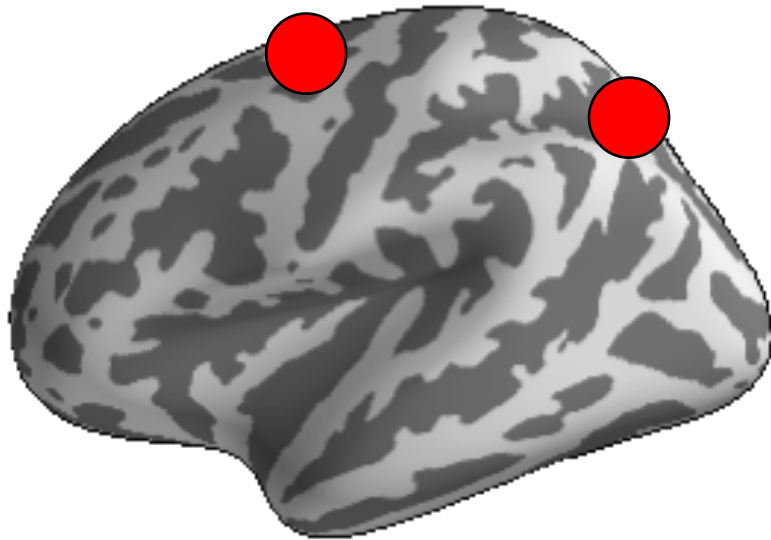
Feedback (2 s)







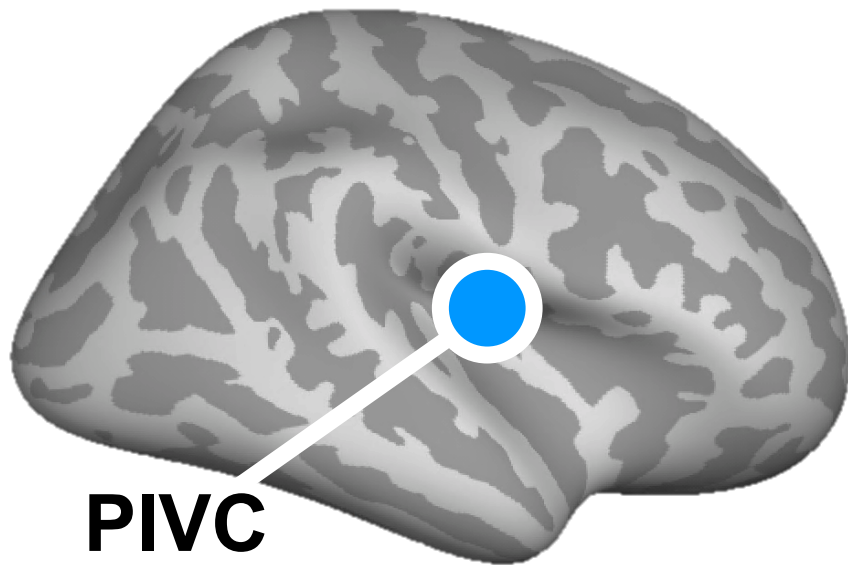
# Fronto-Parietal Attention Network



Culham et al. 2001 Neuron  
Jovicich et al. 2001 JOCN  
Tomasi et al. 2006 HBM  
Frank et al. 2016 Journal of Neuroscience

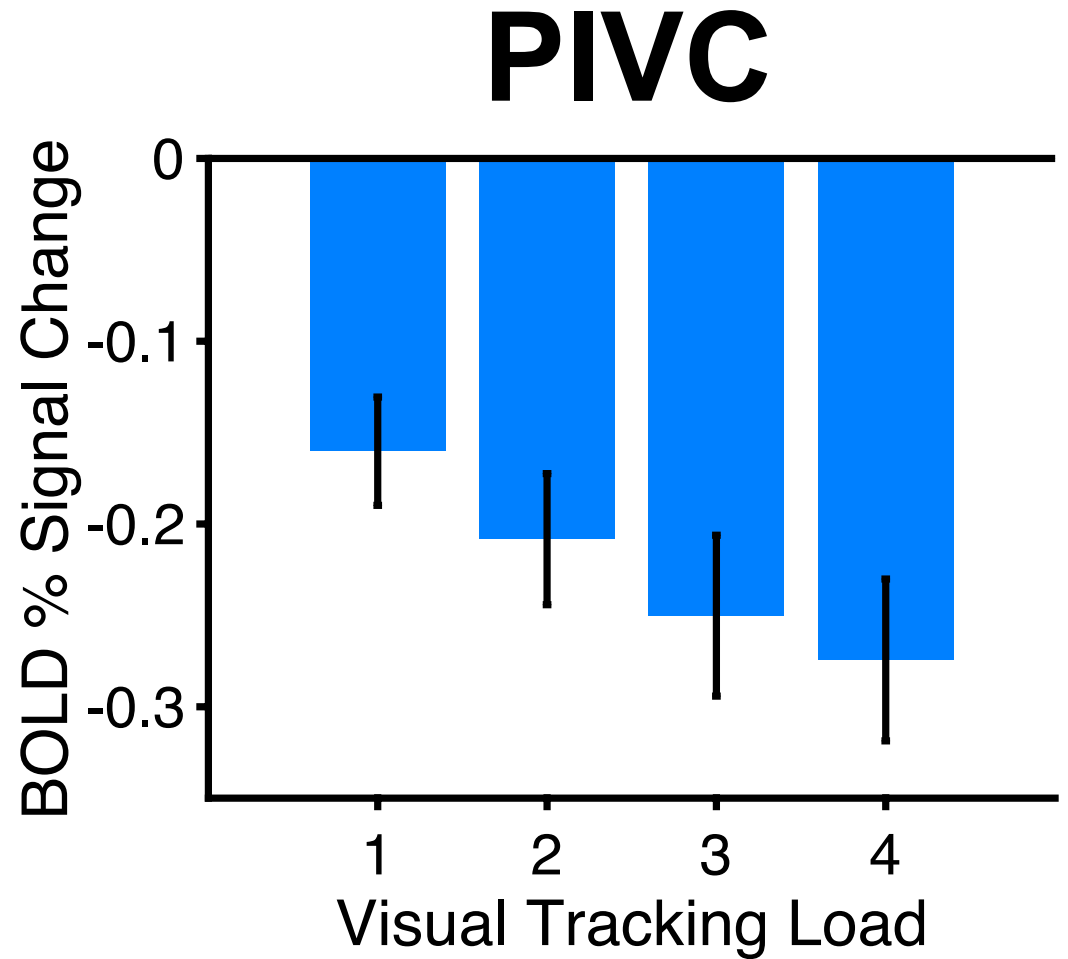


# PIVC Deactivations



PIVC

N = 20  
subjects



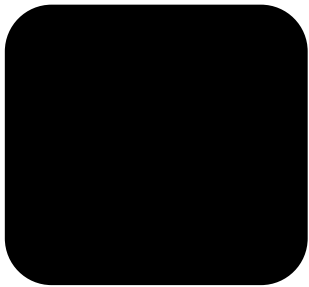
# Follow-up Questions

- Visual attention cross-modally influences activity in the vestibular cortex.
- Does visual attention also influence vestibular sensations of self motion?

# Visual Attention Suppresses Vestibular Sensations

a)

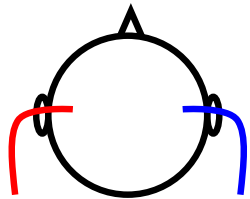
Eyes  
Closed



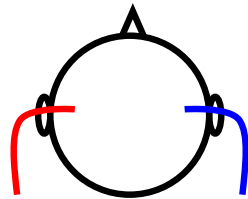
Passive  
Viewing



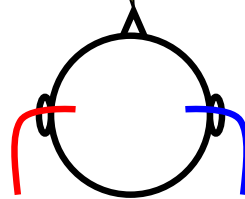
Attentive  
Tracking



Vestibular  
Stimulation



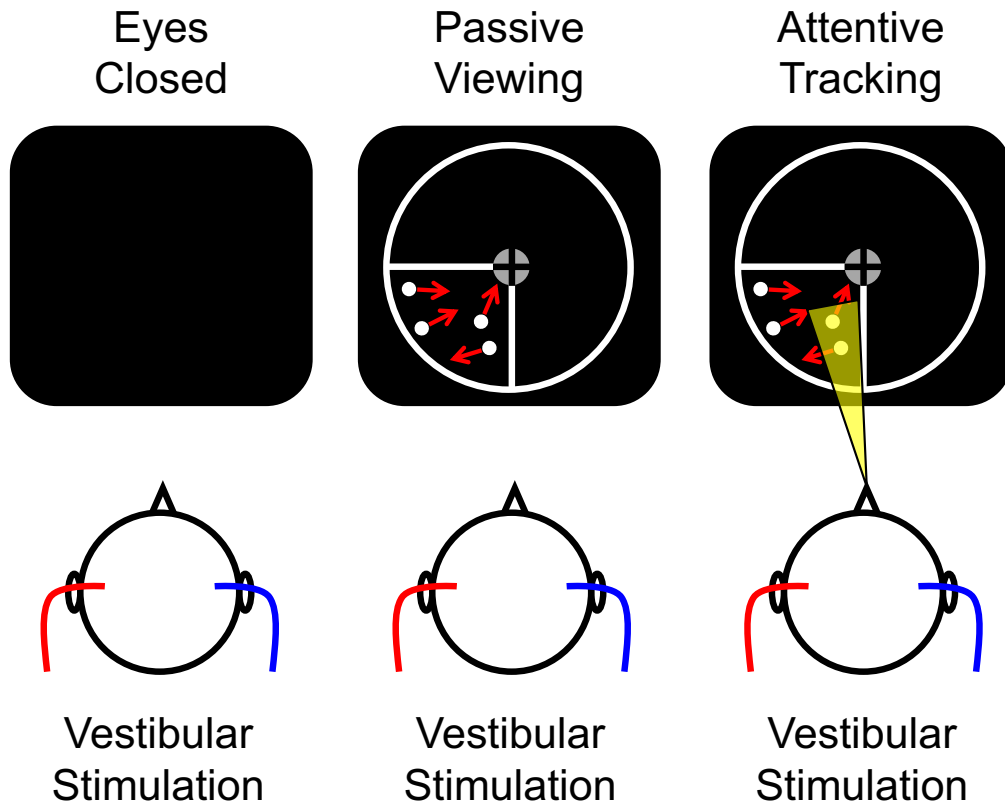
Vestibular  
Stimulation



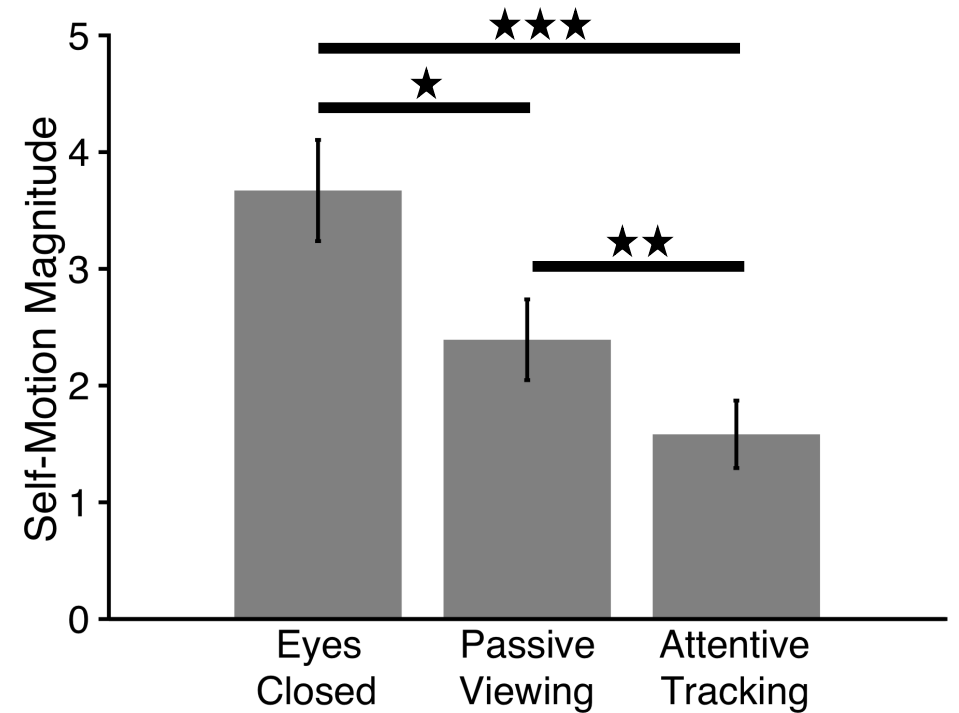
Vestibular  
Stimulation

# Visual Attention Suppresses Vestibular Sensations

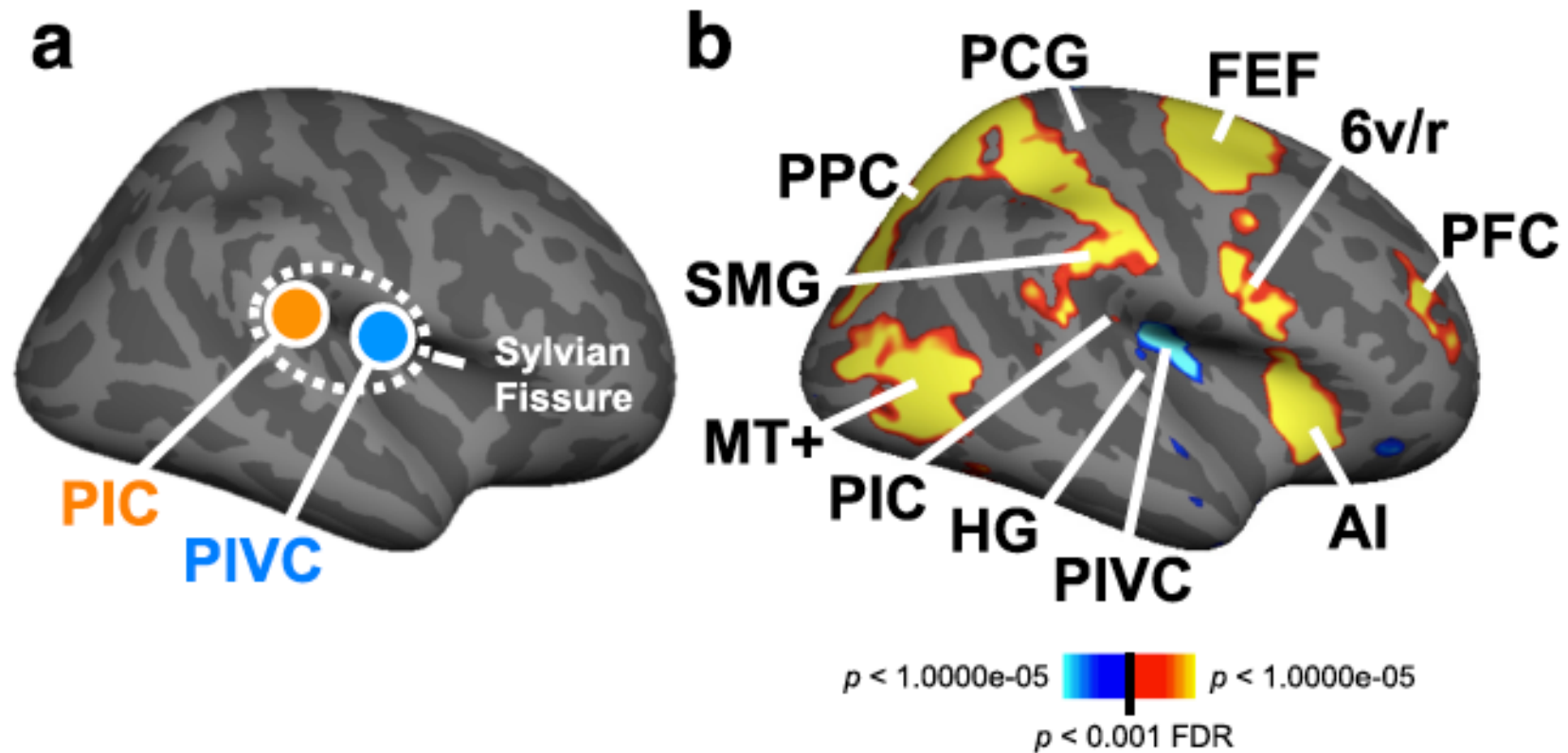
a)



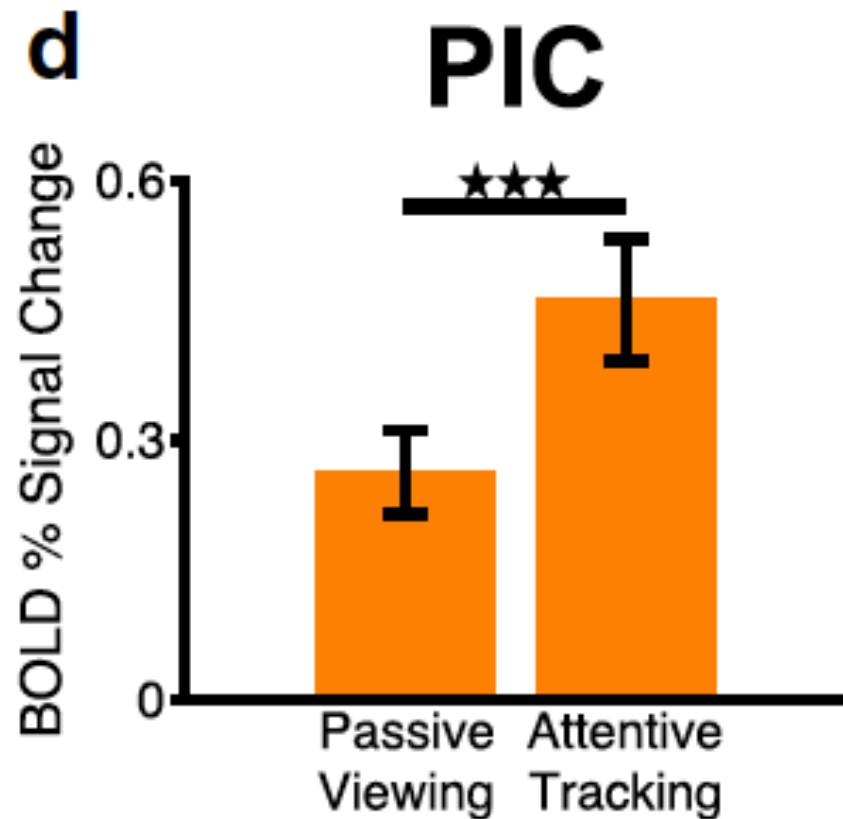
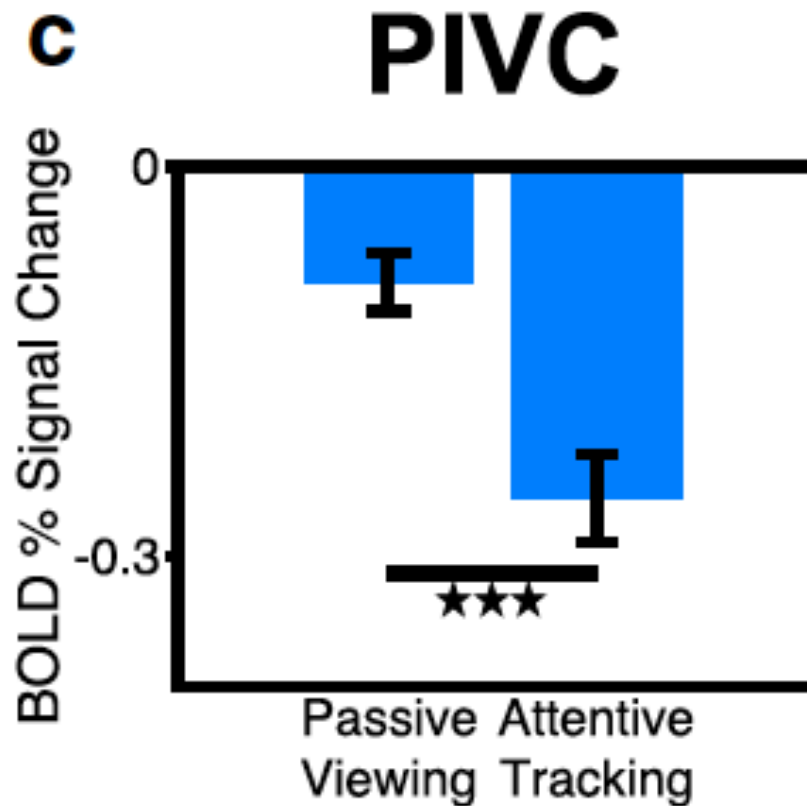
b)



# BOLD Activations during attentive tracking



# BOLD Activations during attentive tracking



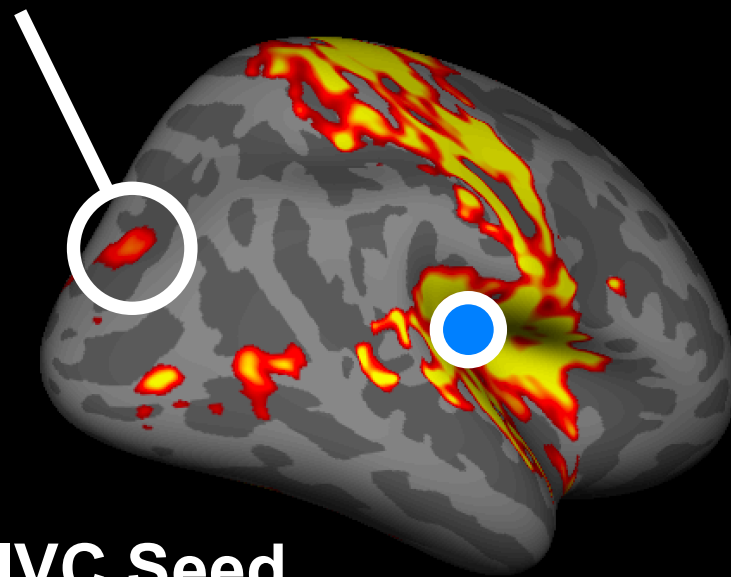
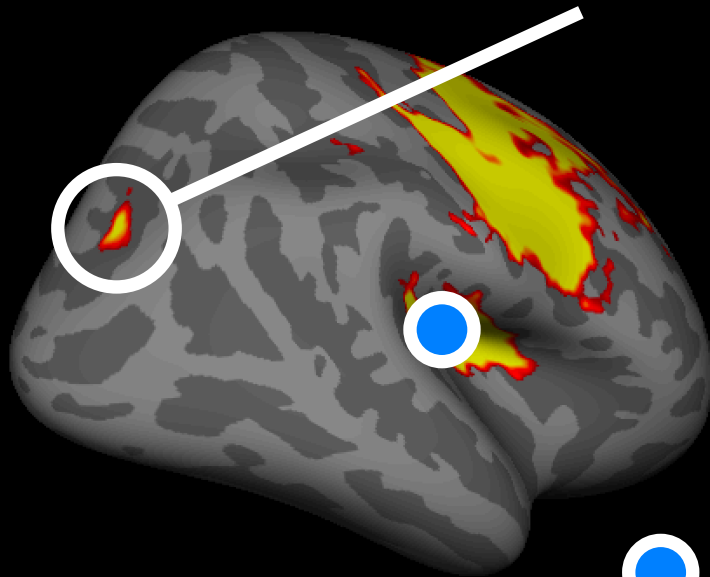
# Follow-up Questions

- Where in the brain does the inhibition by visual attention originate?
- *Posterior Parietal Cortex*

**b) Structural Connectivity of PIVC**

**c) Functional Connectivity of PIVC**

**Posterior Parietal Cortex**



**● = PIVC Seed**

*P*track .25  *P*track .30

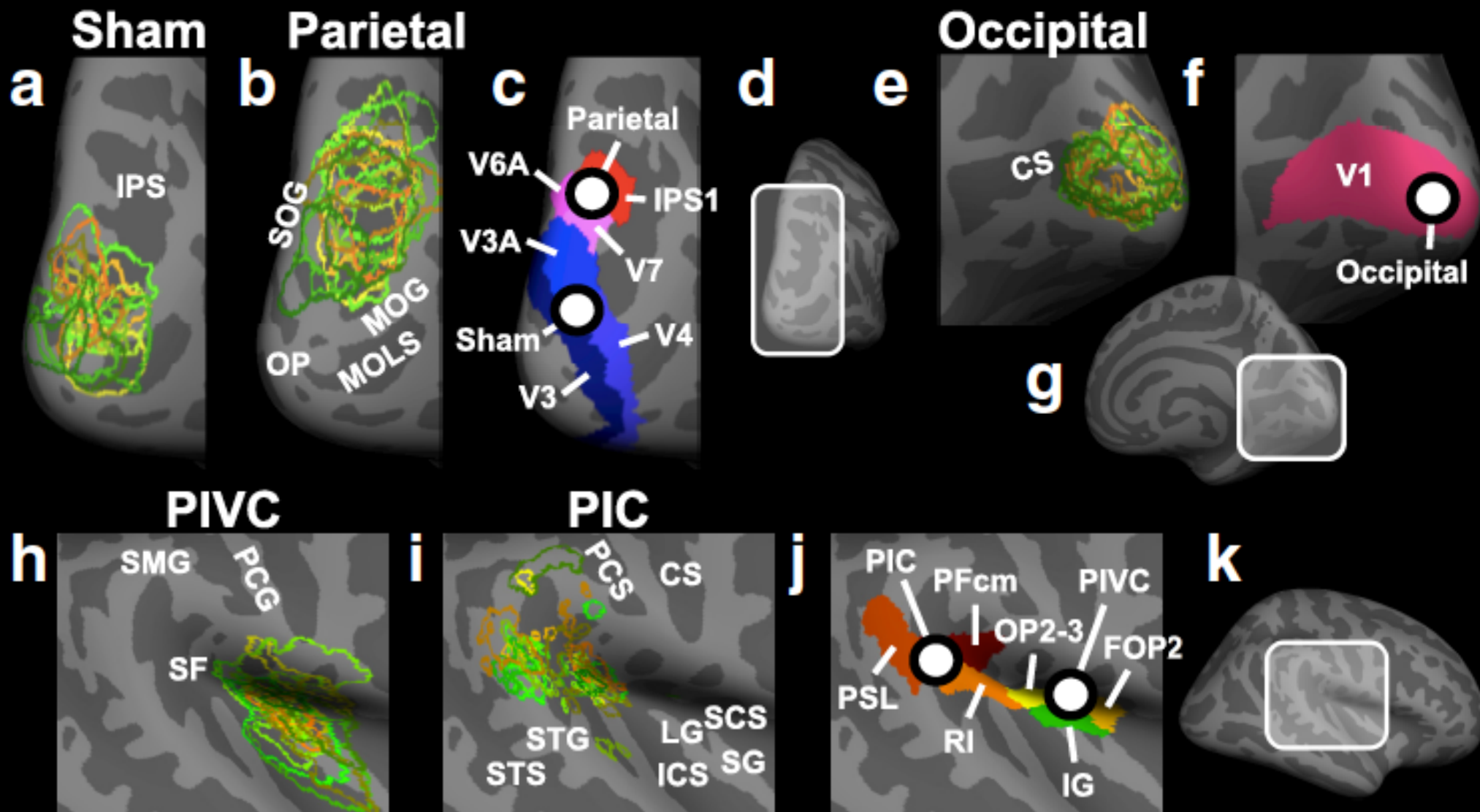
$p < 0.001$  FDR   $p < 1.0000e-05$

**N = 20 subjects**

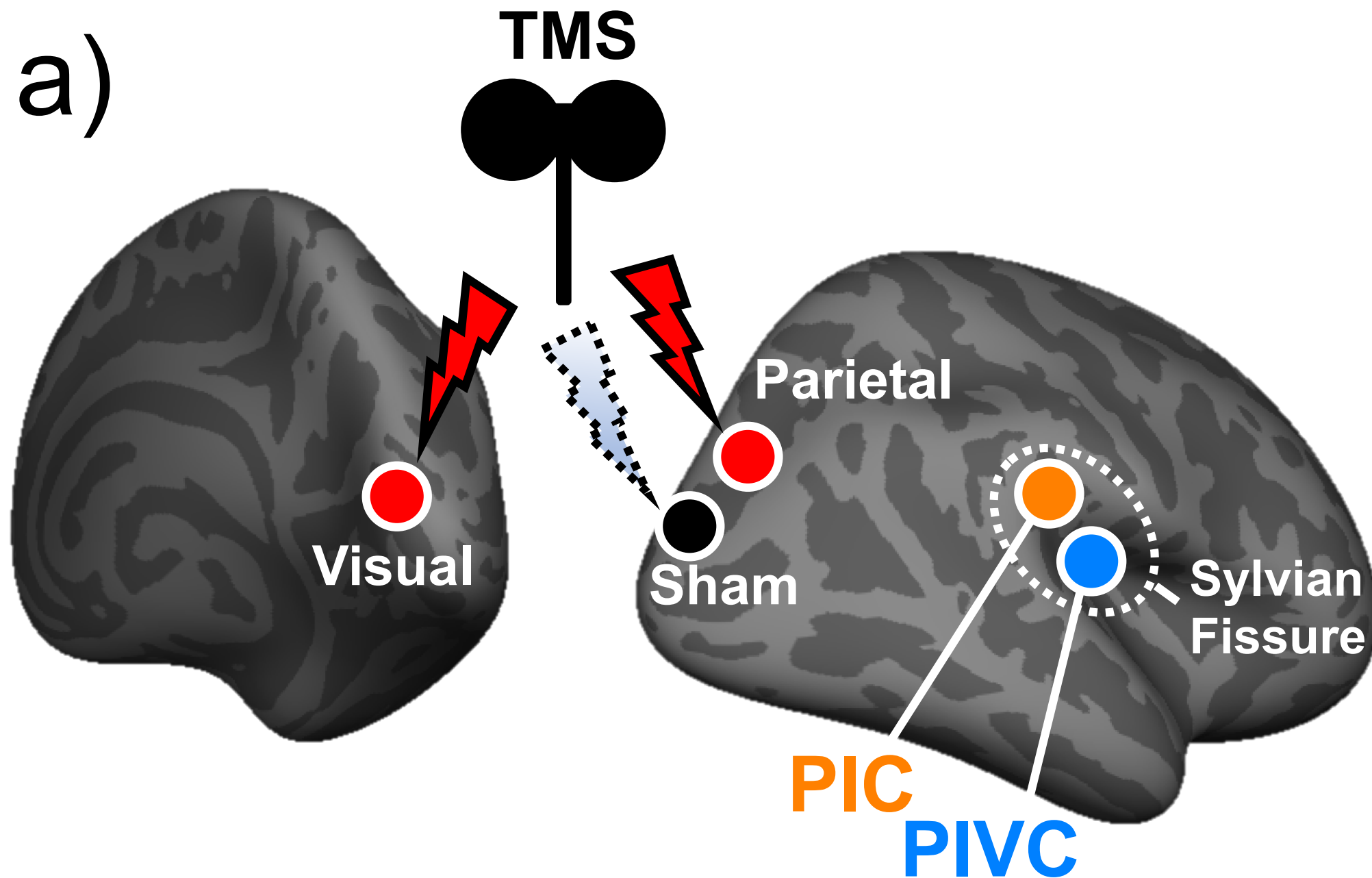
Frank et al., (2020)



# TMS: Regions of Interest

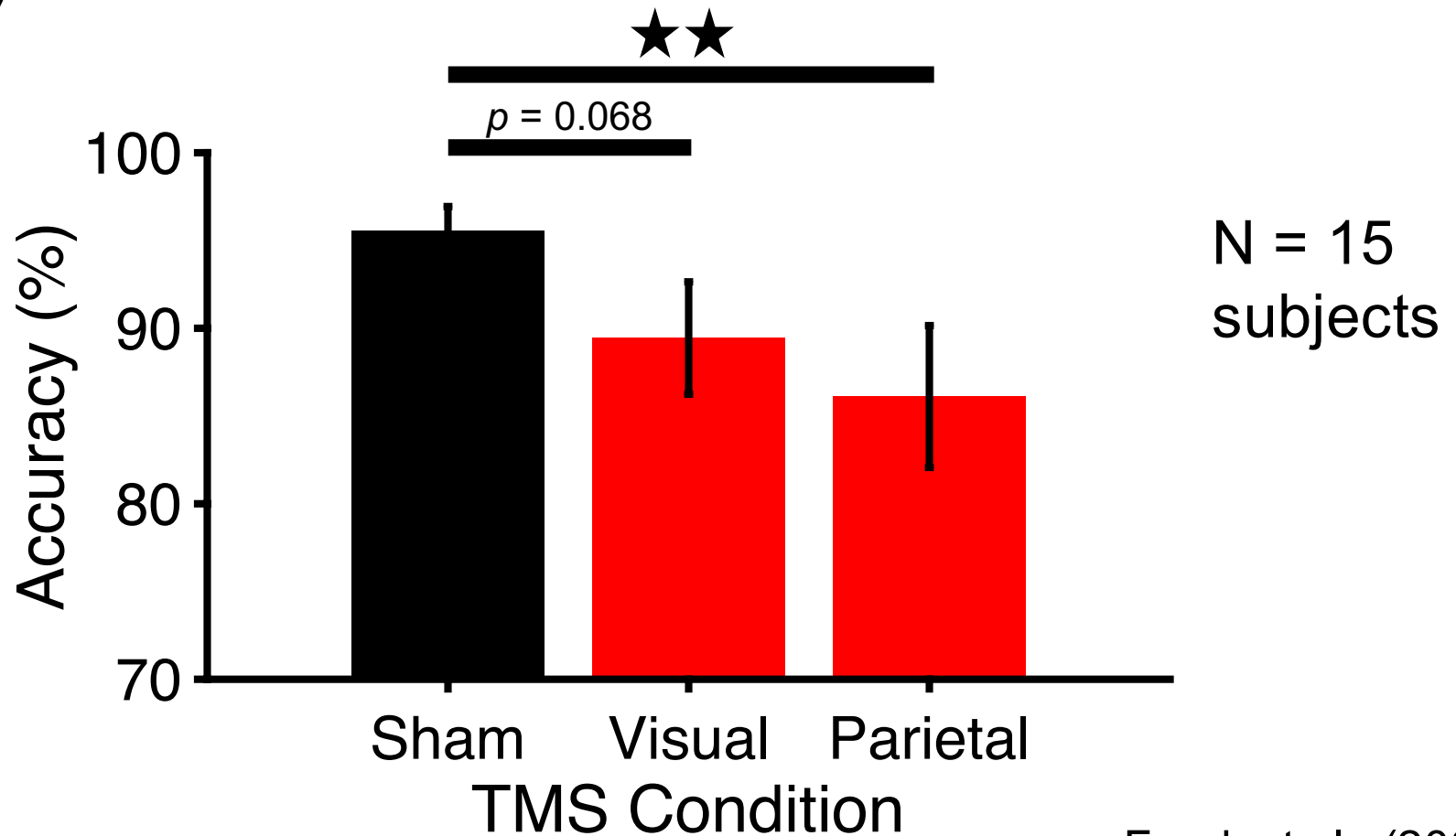


a)

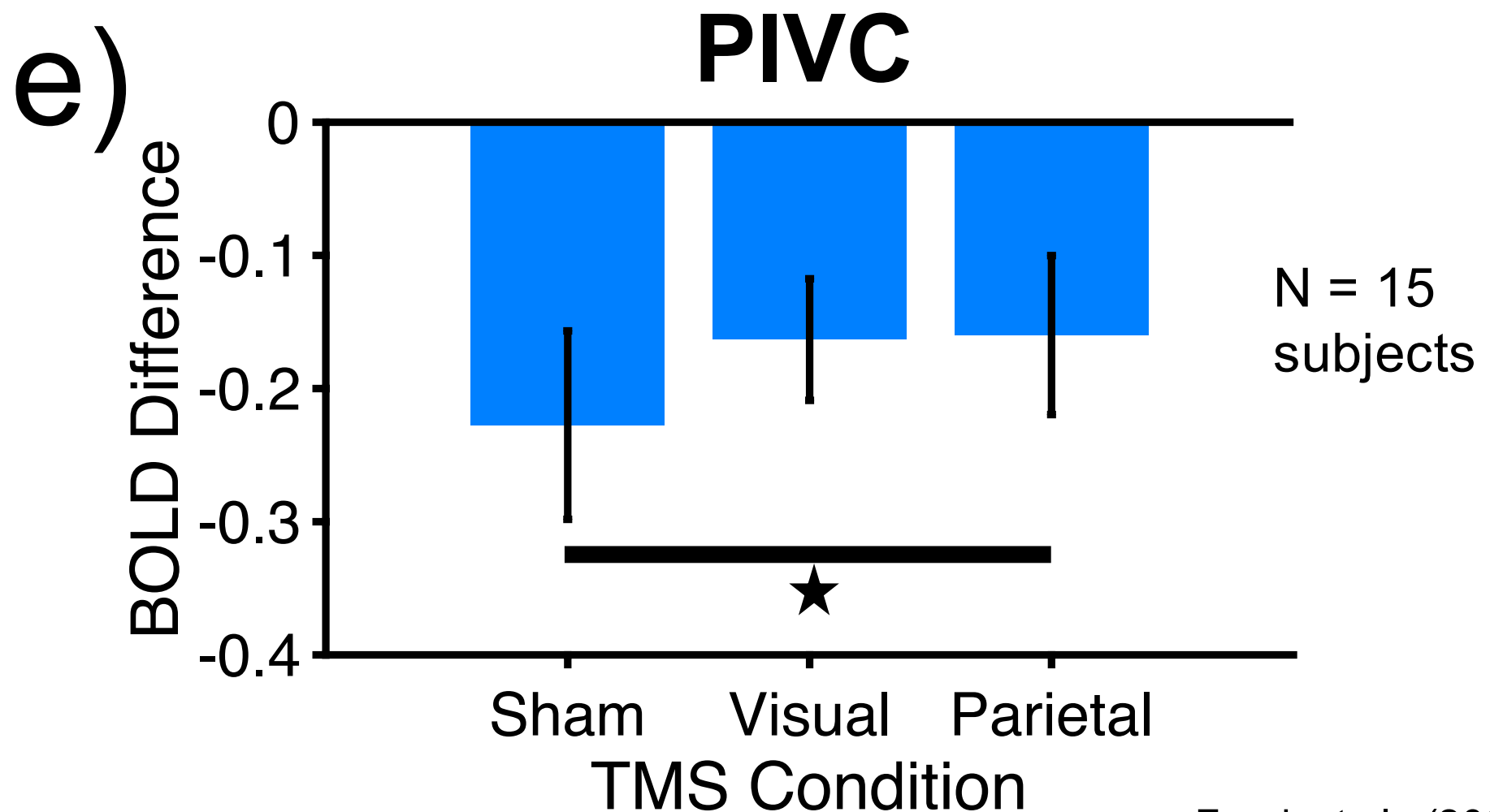


# Behavioral Effects of Inhibitory rTMS

b)

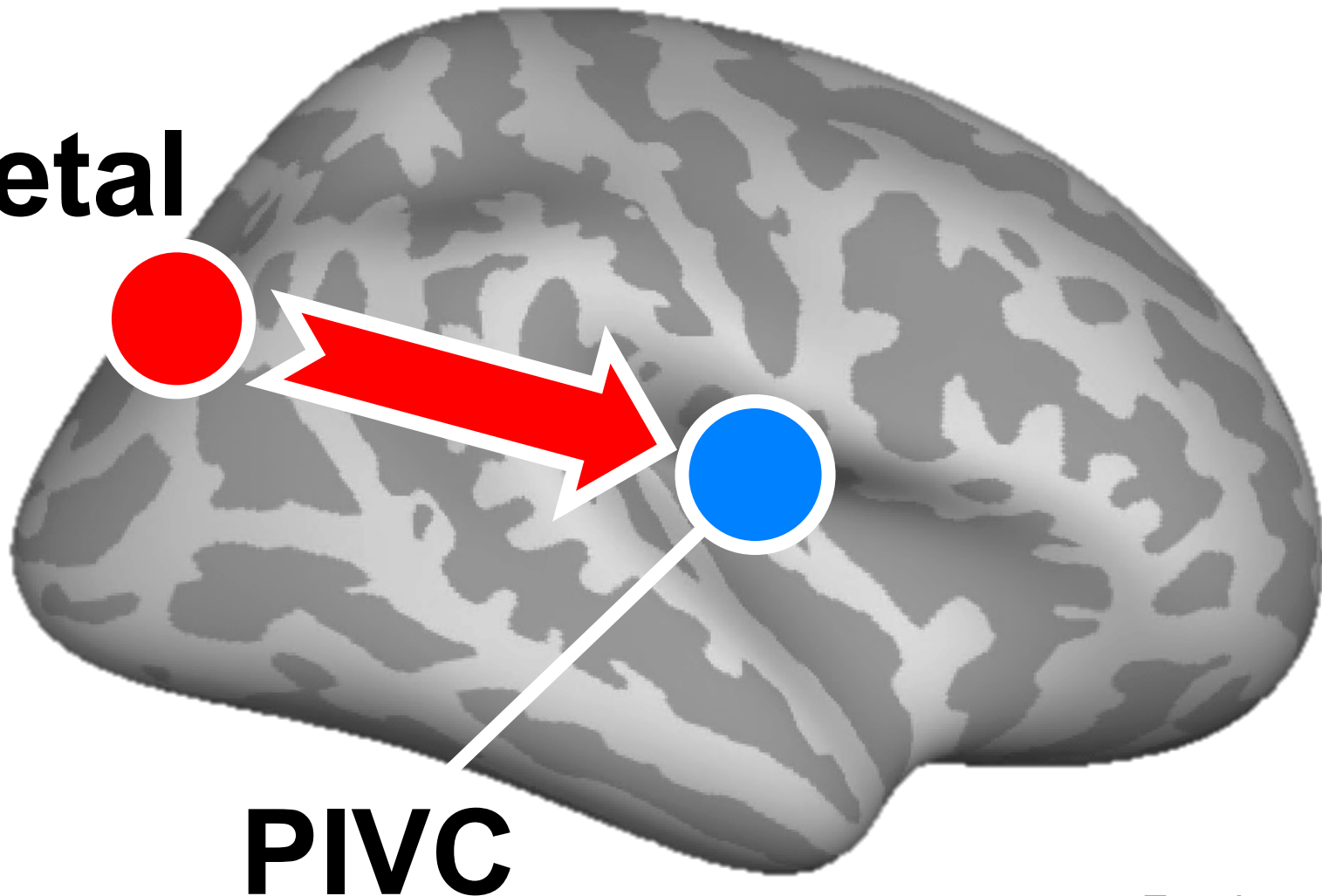


# Neuronal Effects of Inhibitory rTMS



# Inhibition by Visual Attention

**Parietal**



**PIVC**

# Research Issues

1. Inhibition of the vestibular system by visual attention
2. **Biochemical effects of inhibition by visual attention**

# Hypotheses

Inhibition of PIVC is reflected by:

- (1) Decrease of excitatory neurotransmitters
- (2) Increase of inhibitory neurotransmitters
- (3) Combination of (1) and (2)

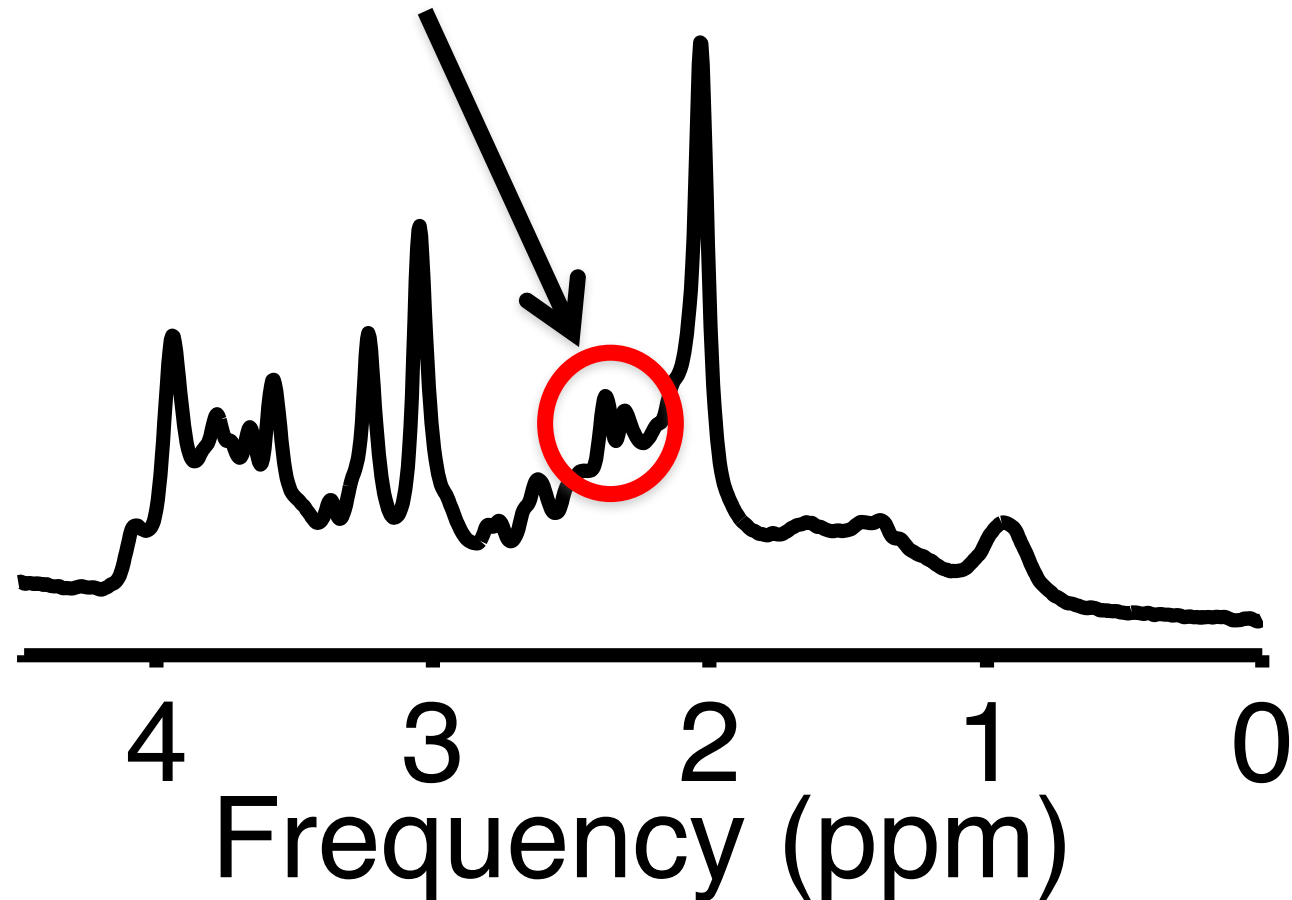
# Magnetic Resonance Spectroscopy (MRS)

- Measures spectrum for a single voxel in the brain (2.5 x 2.5 x 2.5 cm)
- PRESS sequence: Concentration of excitatory neurotransmitter (Glutamate + Glutamine = Glx)
- MEGA-PRESS sequence: Concentration of inhibitory neurotransmitter (GABA)
- Resting-based (MRS) or task-based (fMRS)

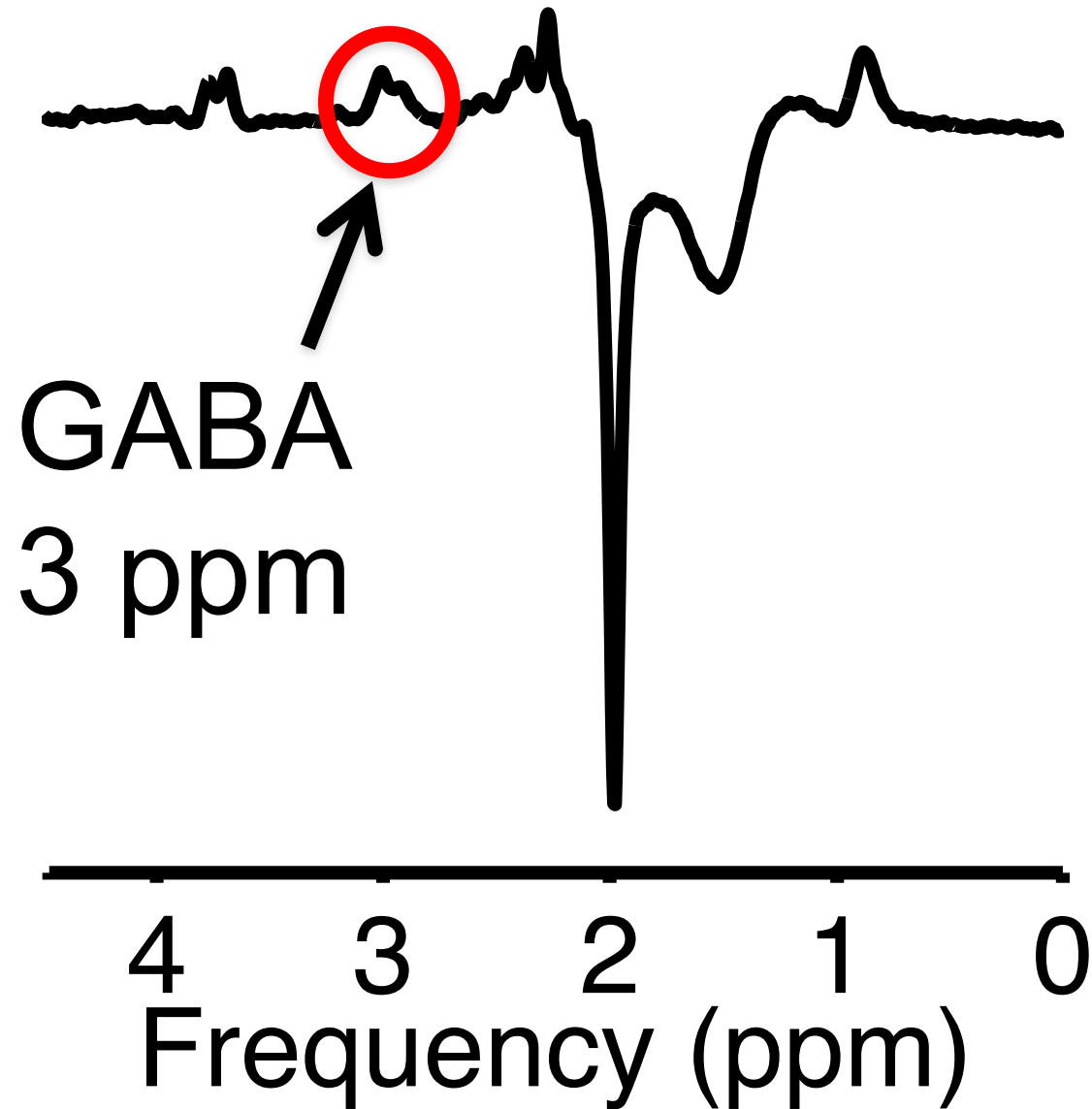


# Example PRESS Spectrum

Glx 2.1-2.5 ppm

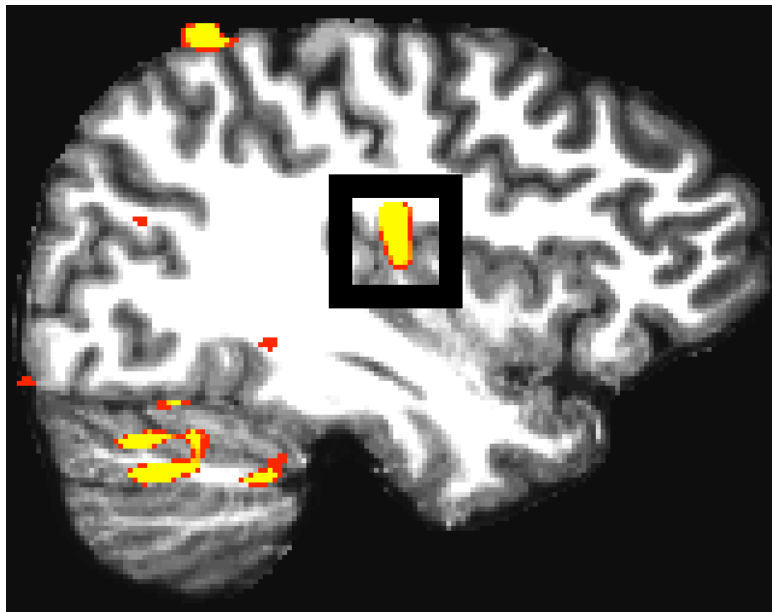


# Example MEGA-PRESS Spectrum



# MRS of Vestibular Cortex

## PIVC



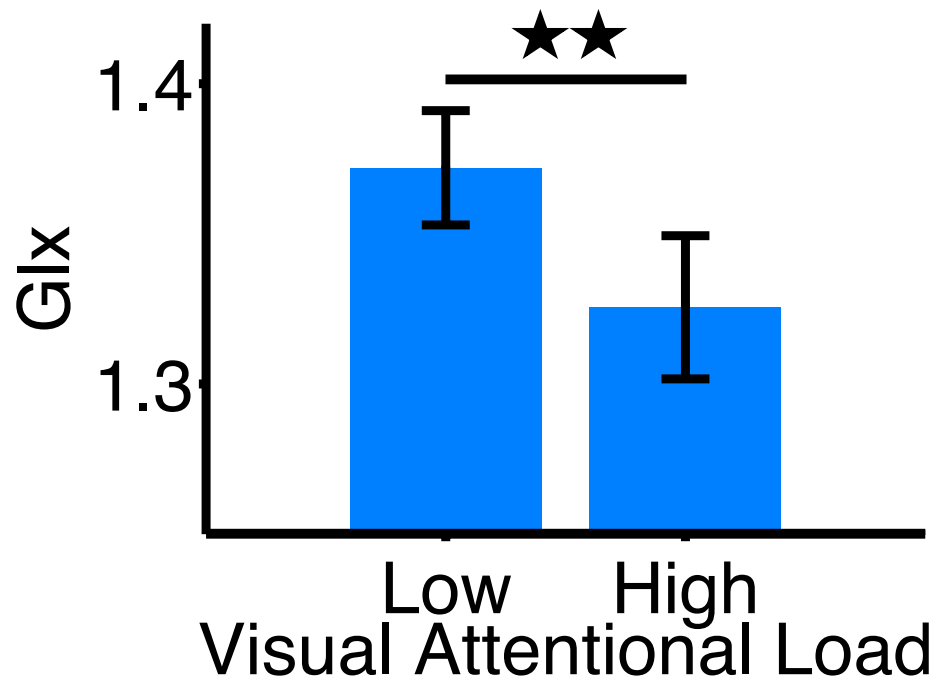
$p < 0.05$  (FDR)   $p < 0.0005$

fMRS in PIVC during:

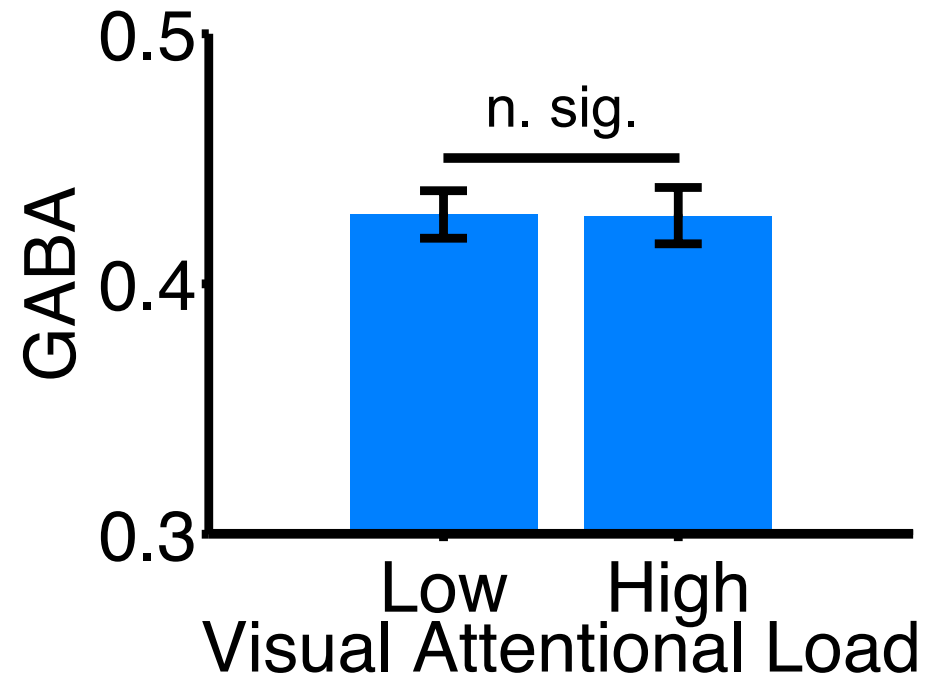
- low visual attentional load (track-2)
- high visual attentional load (track-4)

# Low & High Visual Attentional Loads

## Excitatory NT in PIVC



## Inhibitory NT in PIVC



N = 20 subjects

# Hypotheses

Inhibition of PIVC is reflected by:

- (1) Decrease of excitatory neurotransmitters
- (2) Increase of inhibitory neurotransmitters
- (3) Combination of (1) and (2)

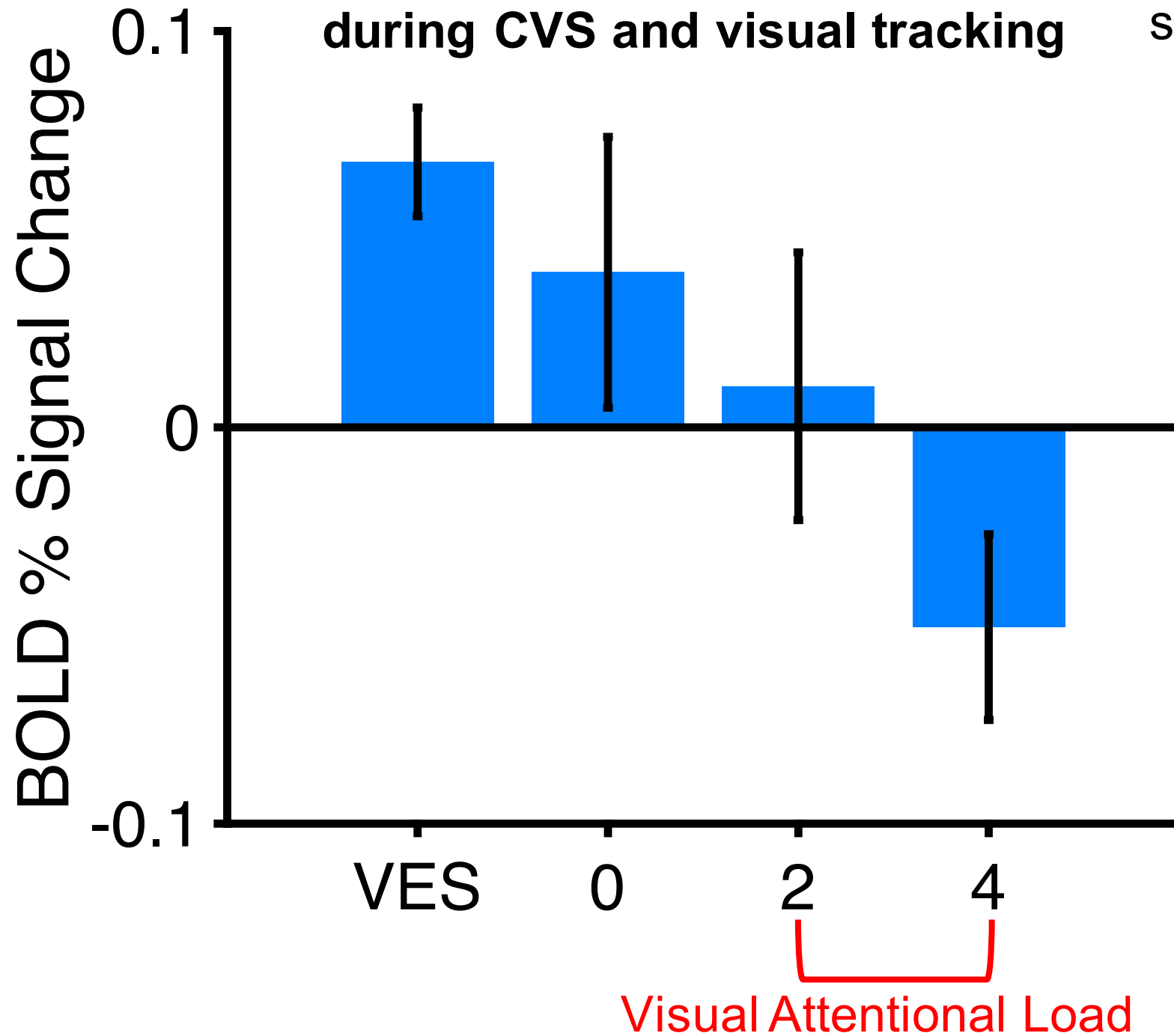
# Follow-up Hypothesis

- Decrease of excitatory neurotransmitter in PIVC renders PIVC less responsive to subcortical vestibular cues
- Visual attentional tracking during caloric vestibular stimulation (BOLD fMRI)

# PIVC Activity

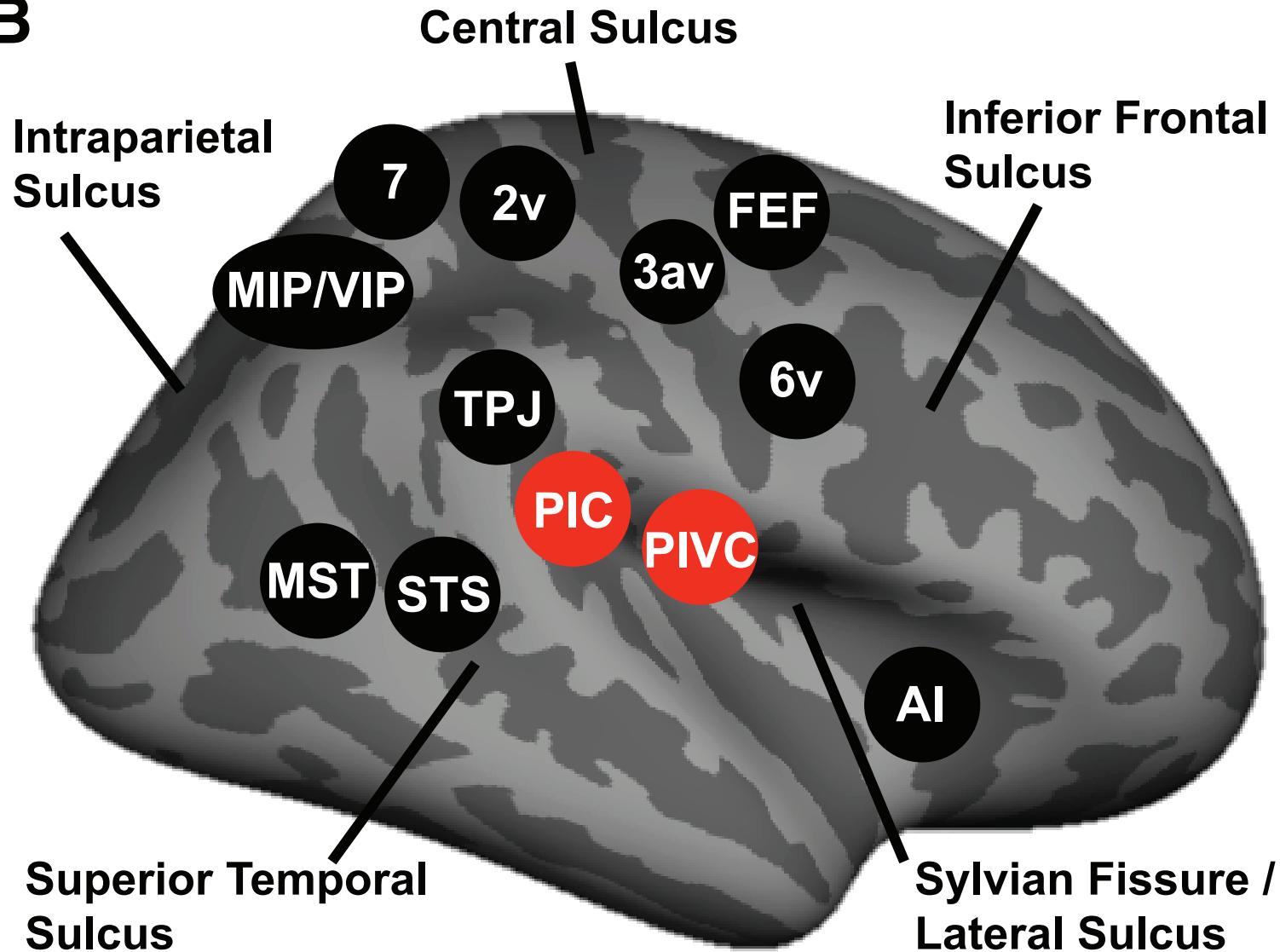
N = 2  
subjects

during CVS and visual tracking



# Vestibular Cortex

**B**





# Thank you for your attention!



Sebastian Frank



Maja Pawellek



Lisa Forster



Wilhelm Malloni



Martin Schecklmann



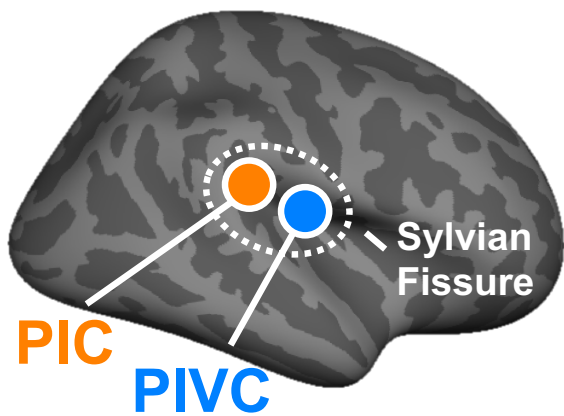
Berthold Langguth

**DFG** Deutsche  
Forschungsgemeinschaft

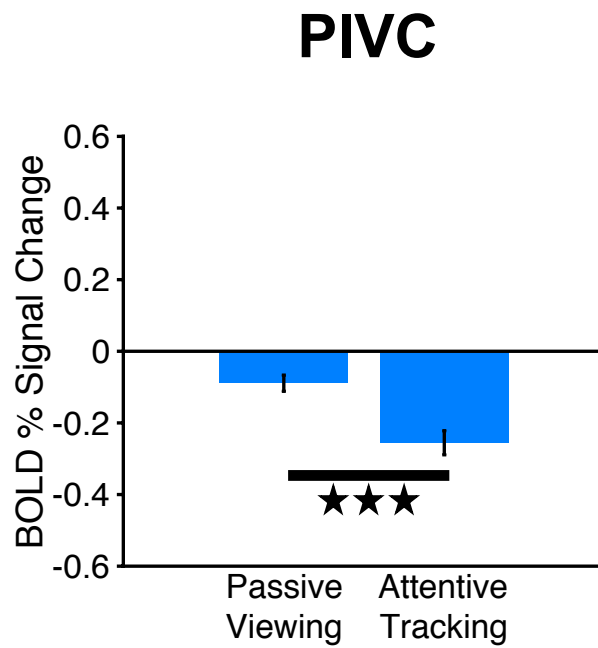
Grant: GR 988 25-1



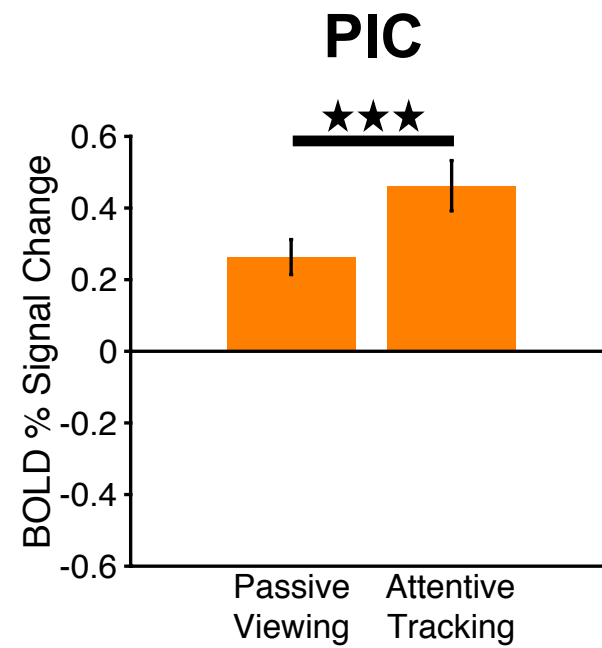
a)



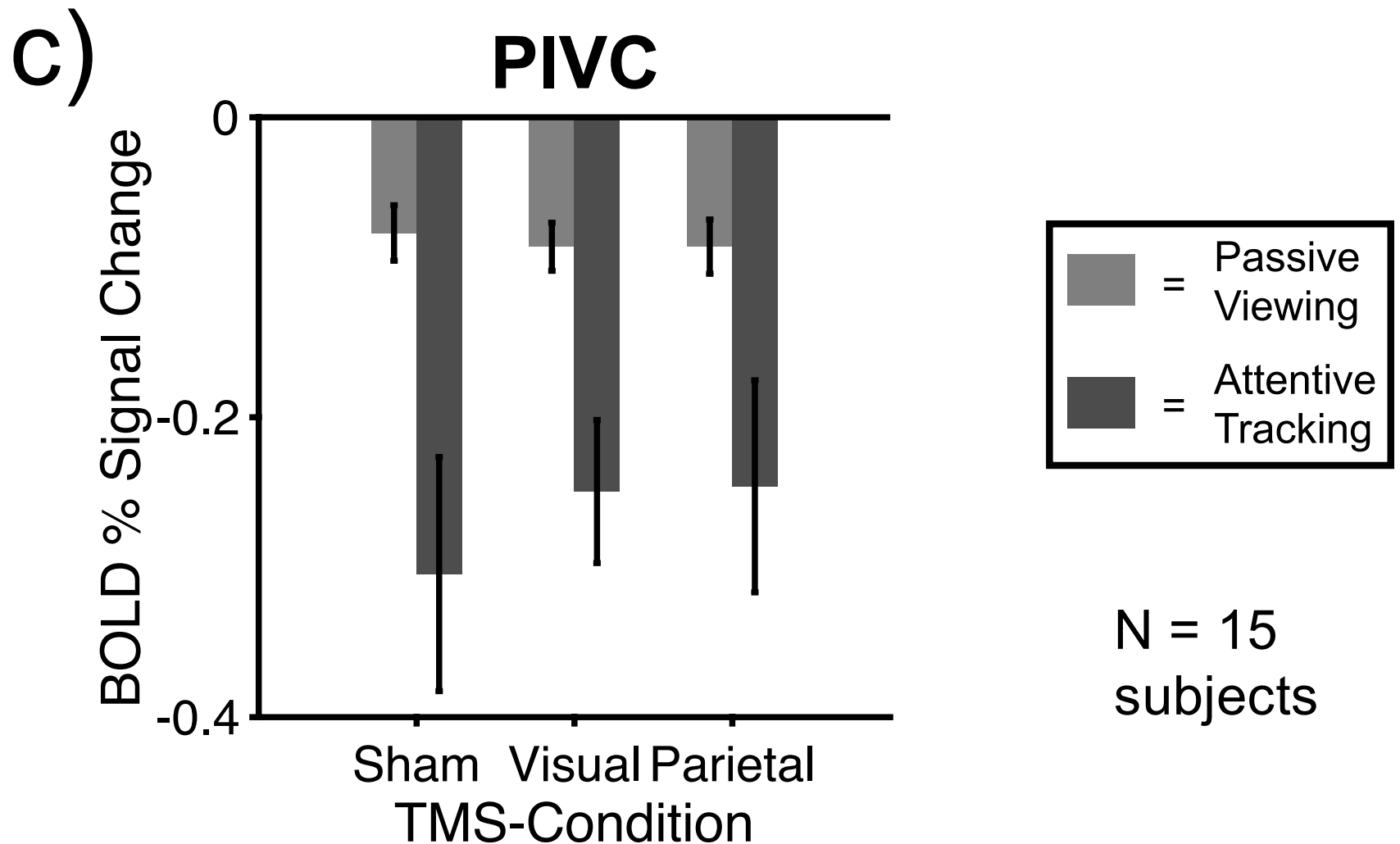
b)



c)



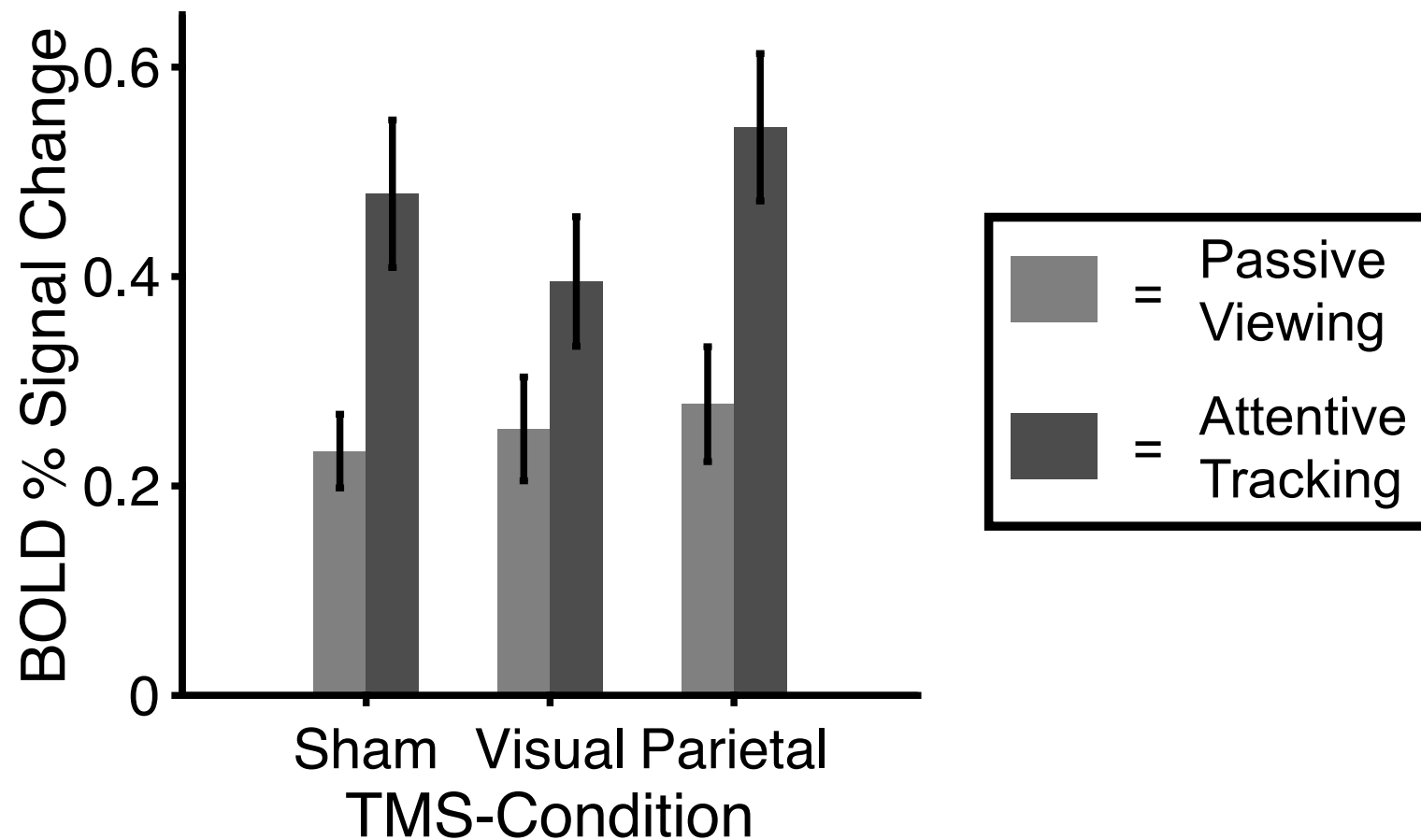
# Neuronal Effects of Inhibitory rTMS



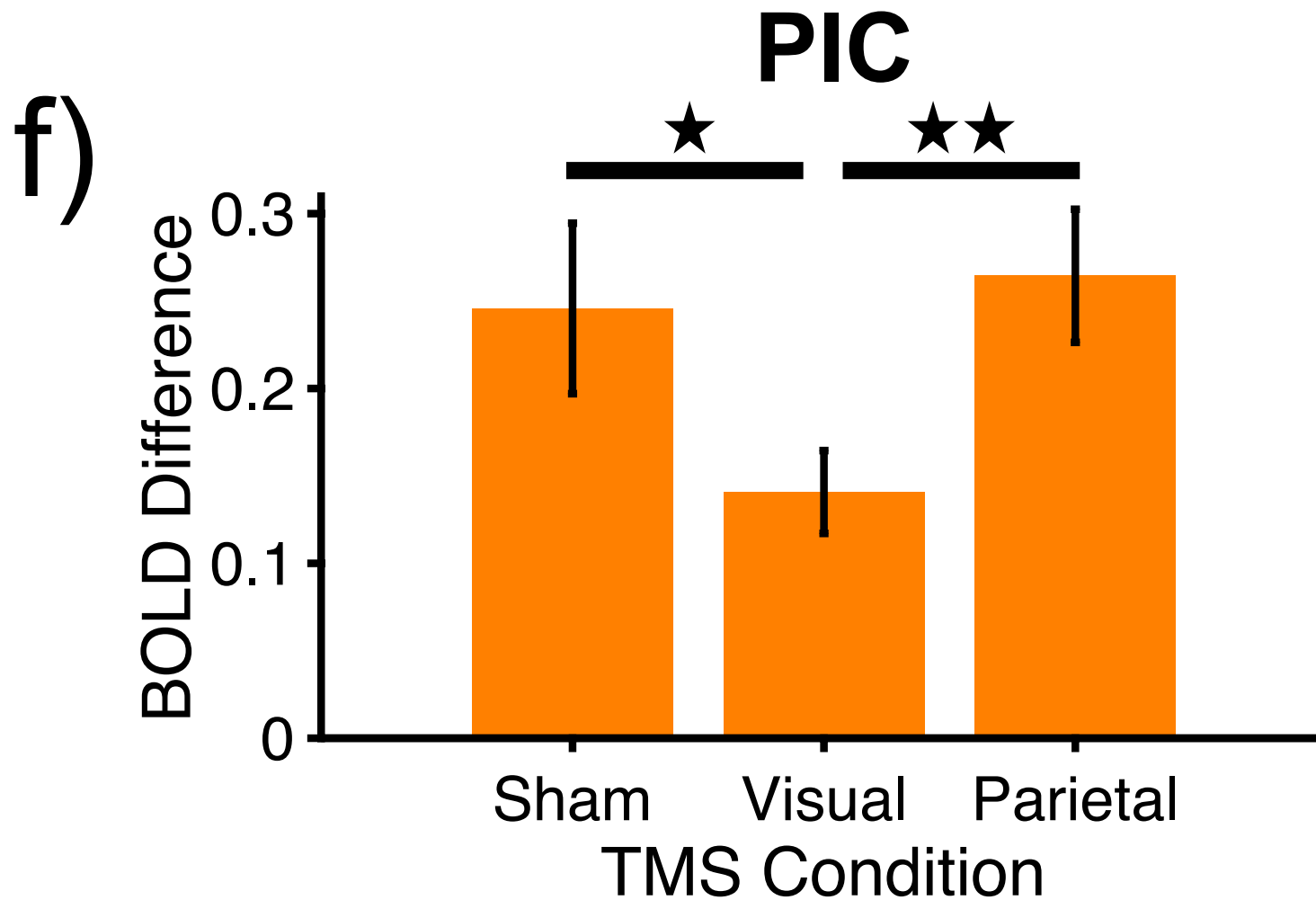
# Neuronal Effects of inhibitory rTMS

d)

**PIC**



# Neuronal Effects of inhibitory rTMS



# Thank you!

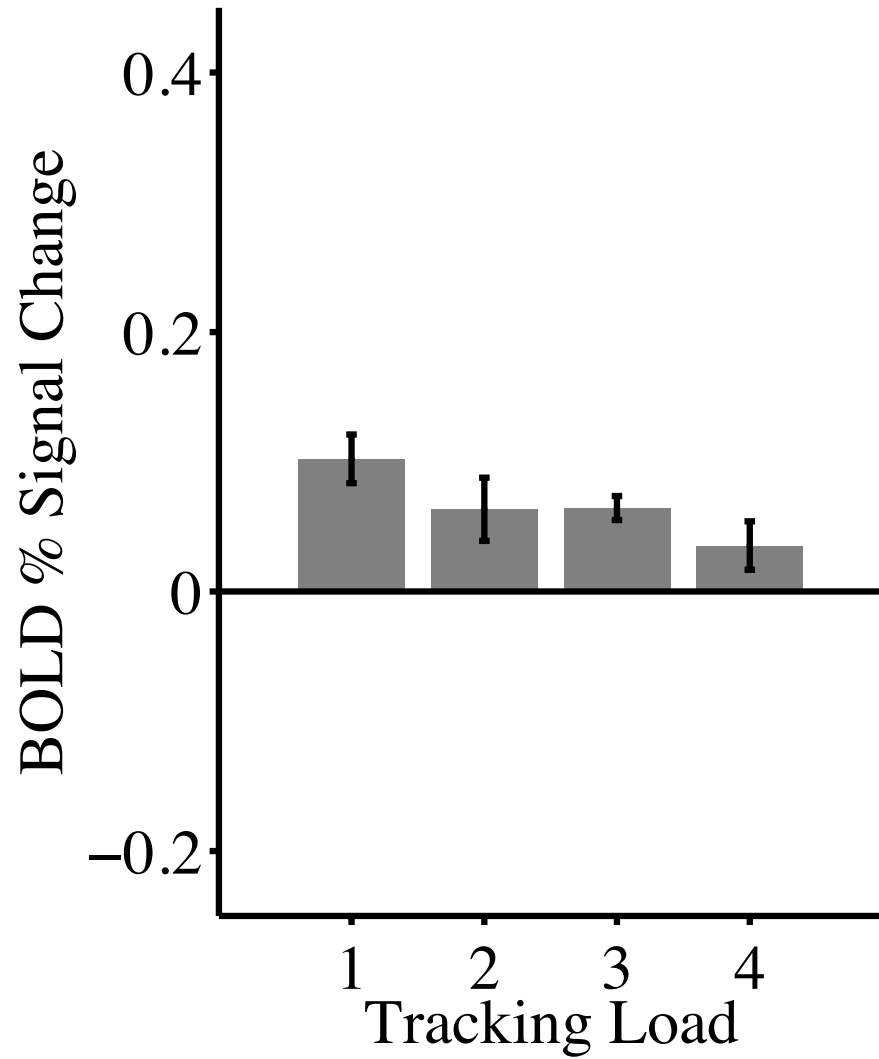




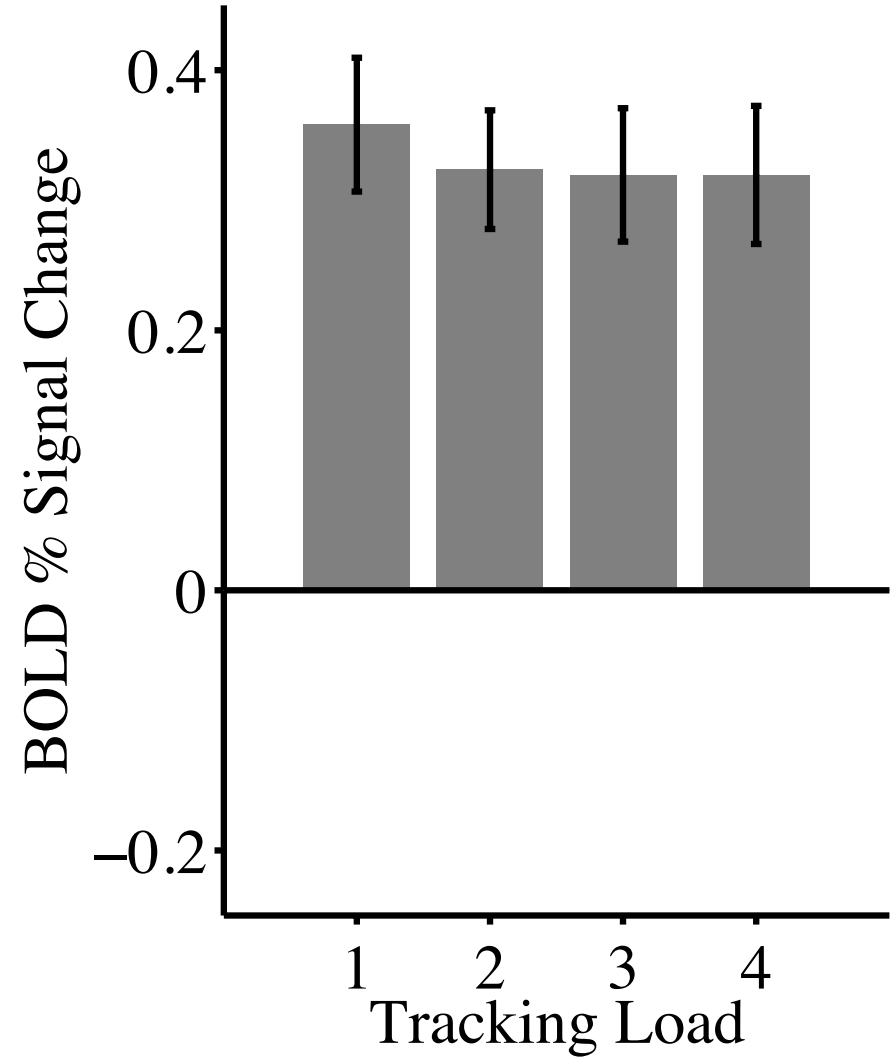


Backup

## PIC anterior

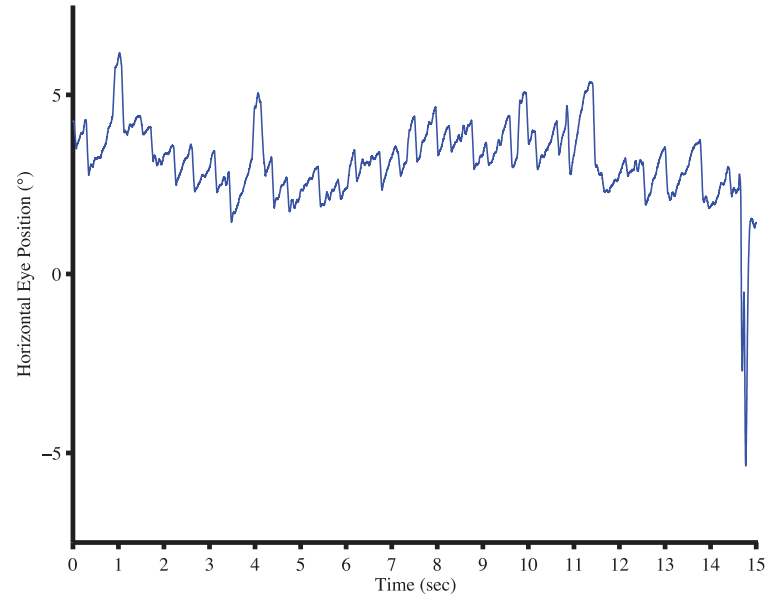


## PIC posterior

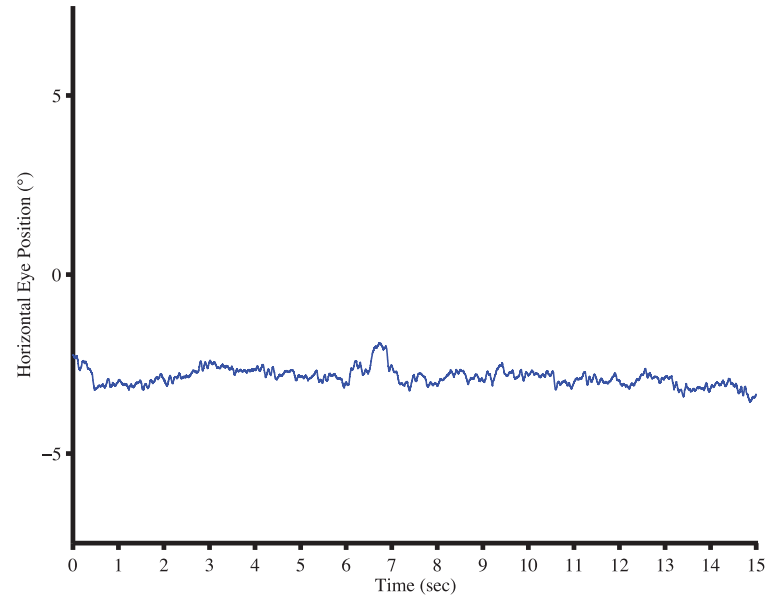


# P1

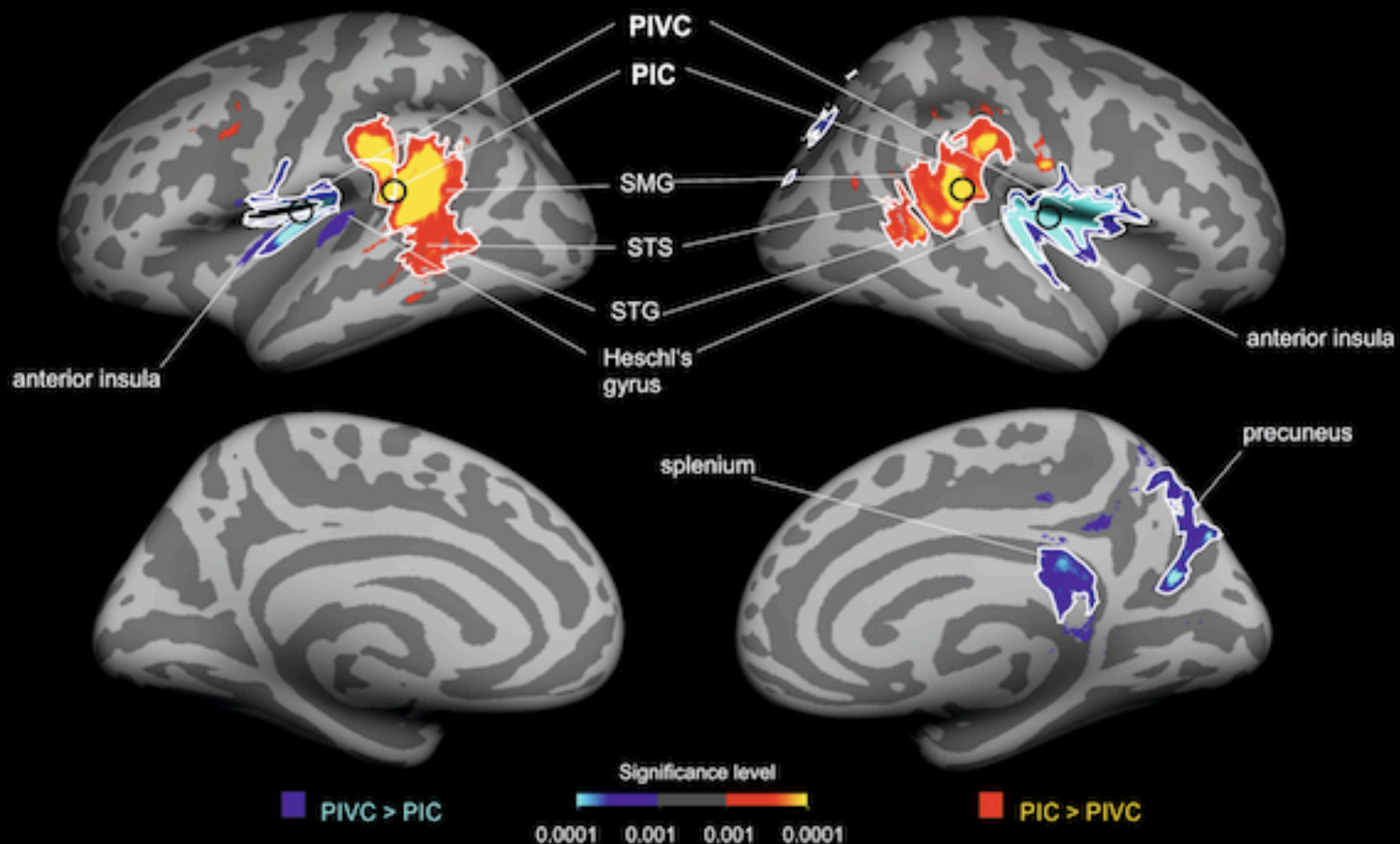
Without Fixation



With Fixation



**C** Significant differences in connectivity profiles between PIVC and PIC ( $n = 15$ )



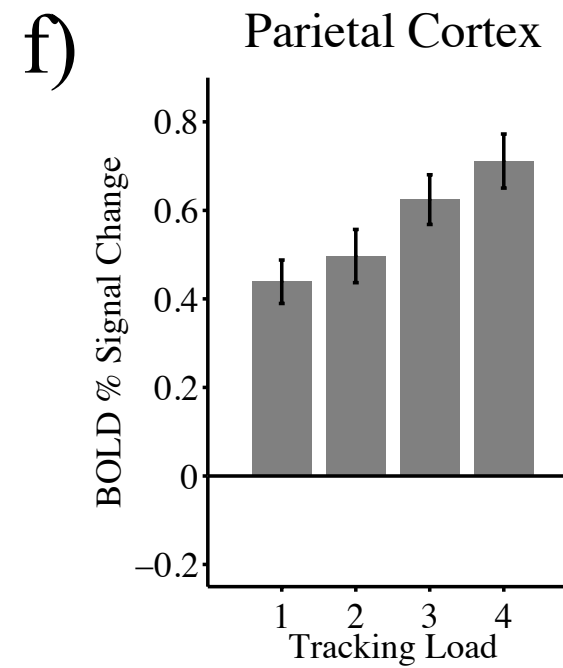
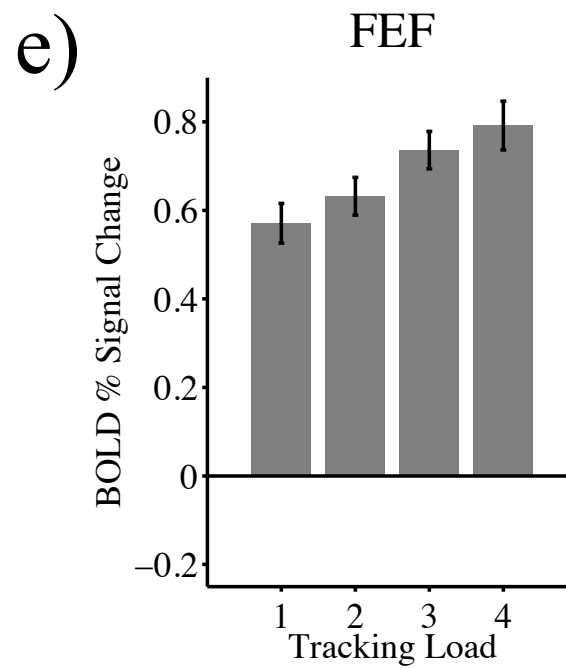
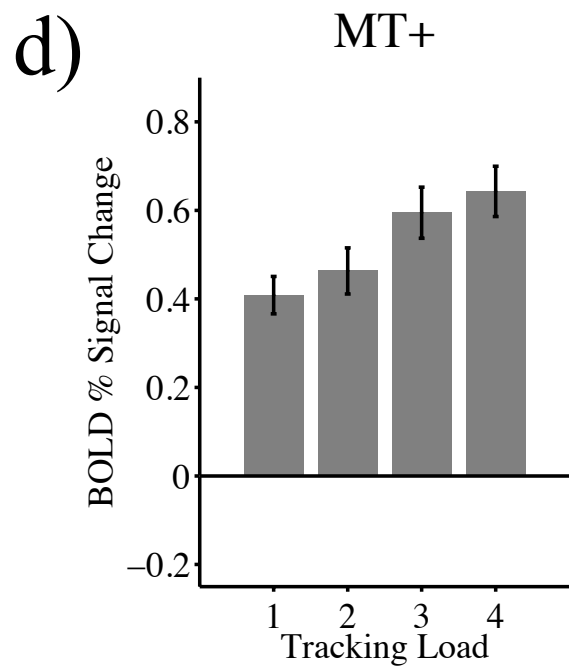
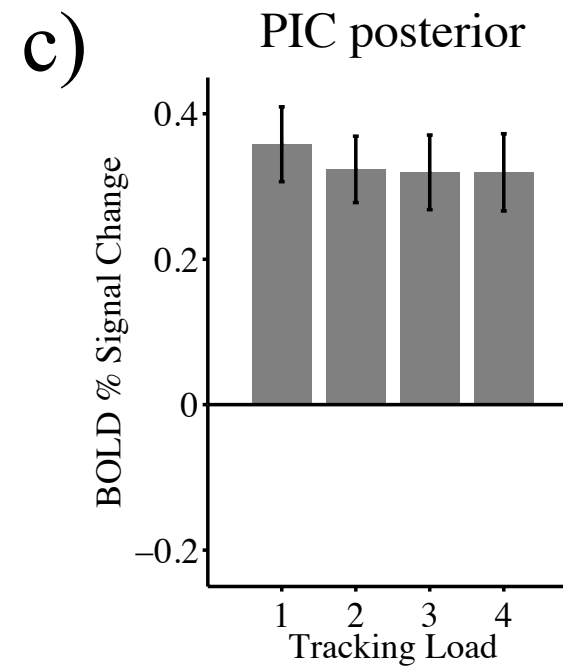
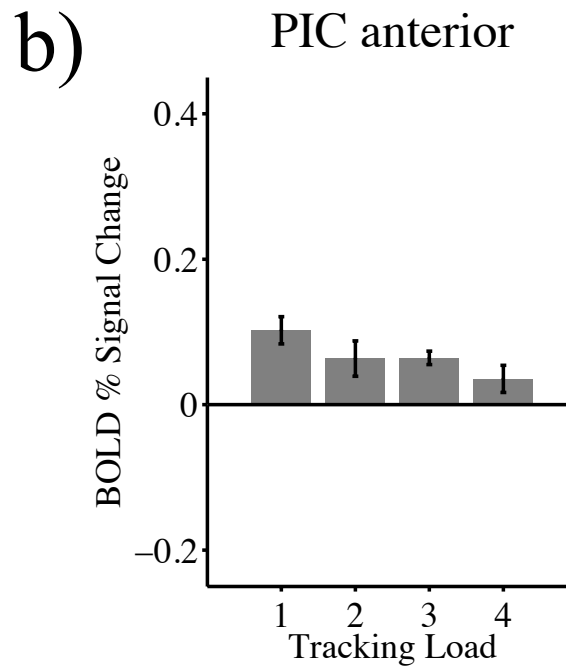
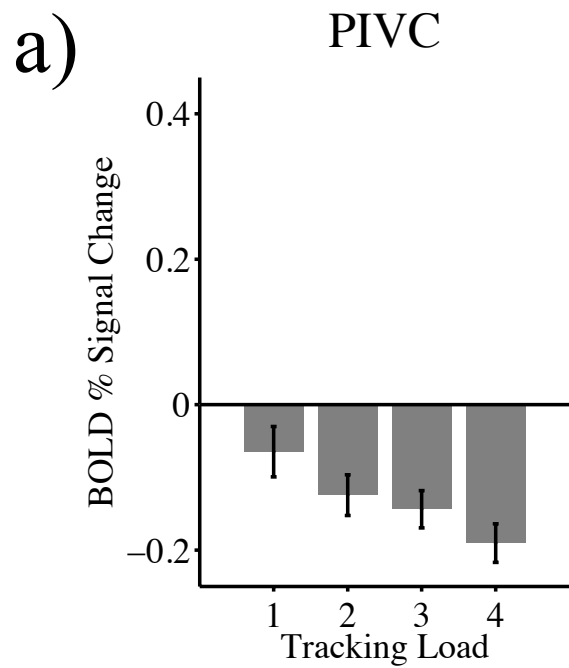




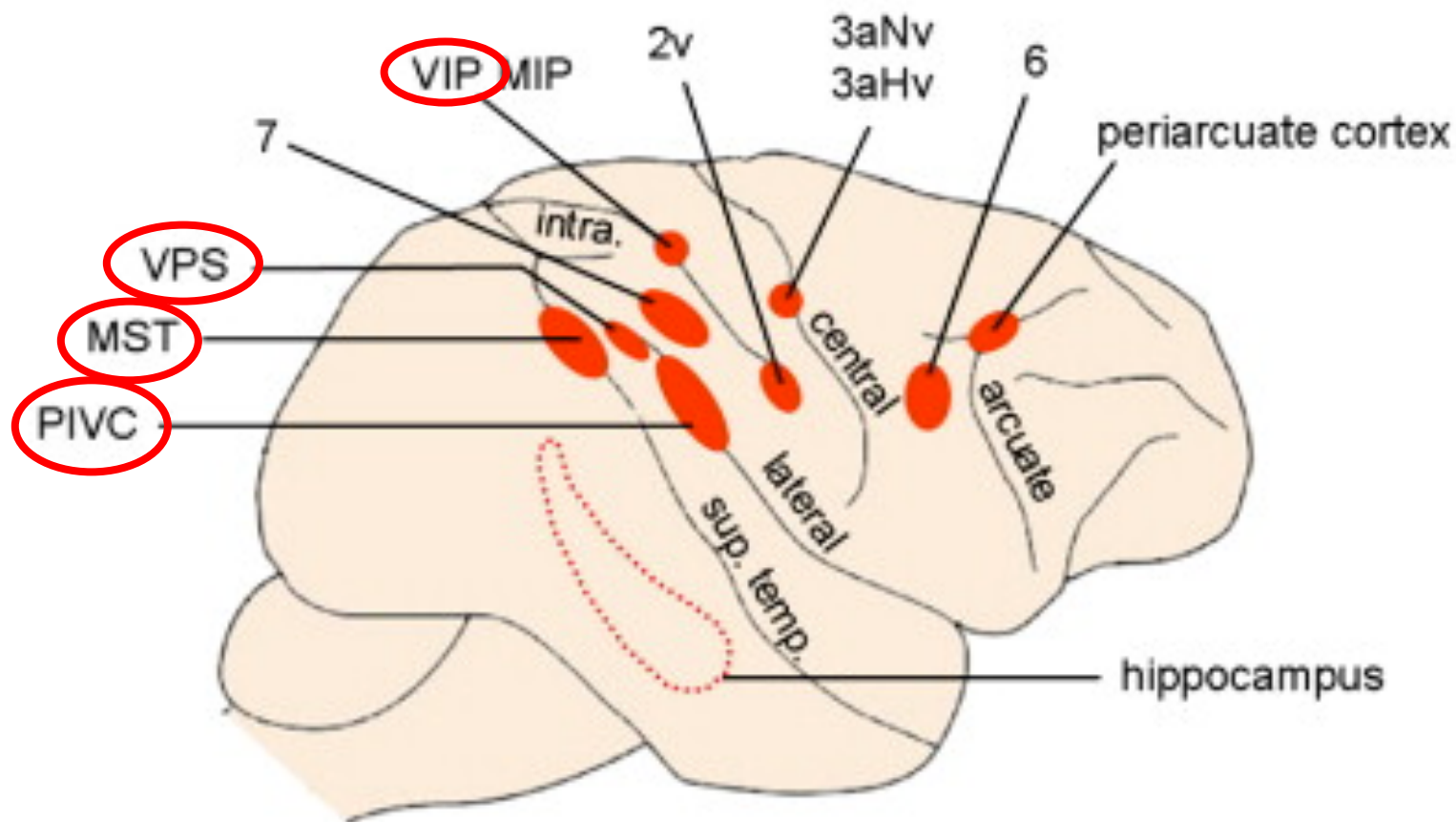








# Cortical Representation



Guldin & Grüsser 1998 Trends Neurosci

Lopez & Blanke 2011 Brain Res Rev

# Cortical Representation

## Primates

- MST (Bremmer et al 1999, Gu et al 2006, 2007, 2008)
- PIVC (Grüsser et al 1990, Guldin & Grüsser 1998, Chen et al 2010)
- VIP (Bremmer et al 2002, Klam & Graf 2003, Chen et al 2011)
- VPS (Guldin & Grüsser 1998, Chen et al 2011)

## Humans

- MST (not MT!, Smith et al 2012)
- PIVC (many indications, see review by Lopez et al 2012)
- VIP (dorsal IPS) & STS ? (trends in Smith et al 2012)
- VPS ?

**Multisensory areas** in human **motion-sensitive** cortex

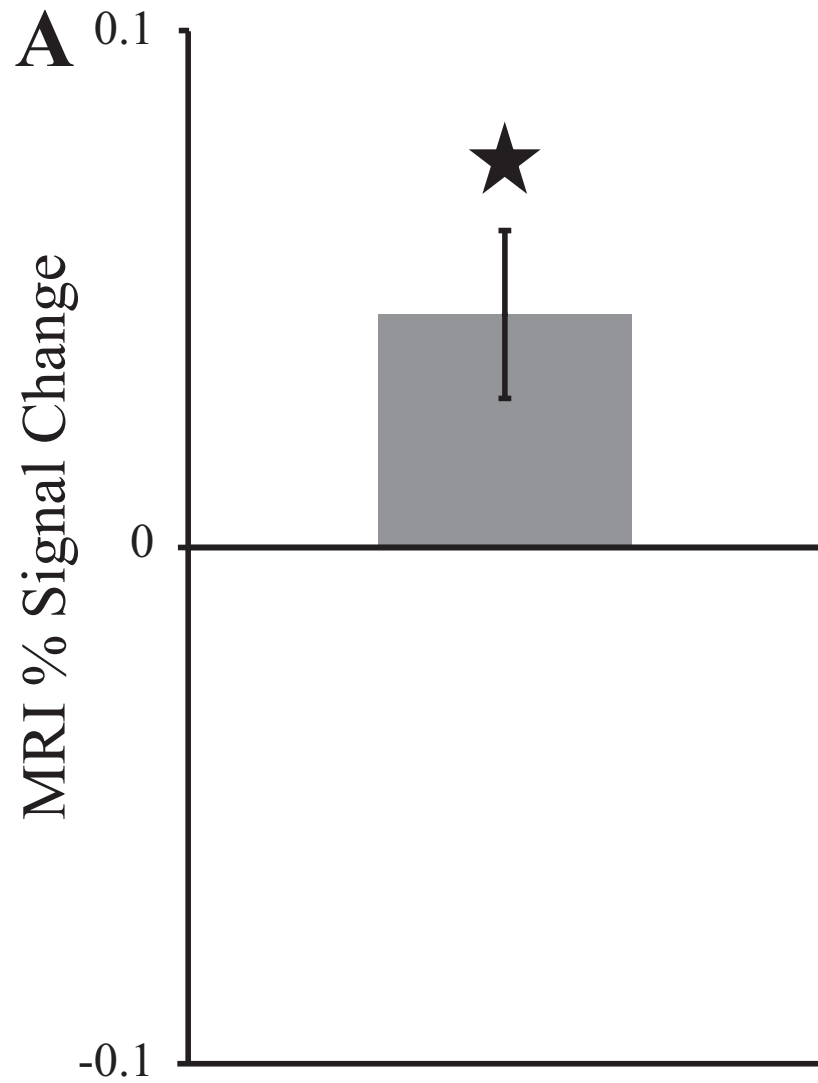
# Goals

- Design MRI-compatible **vestibular stimulation system**
- Combine **visual and vestibular** stimuli
- Vestibular processing in **motion-sensitive cortex** (MST, STS, VIP, VPS)
- Functional specialization within **PIVC complex**: role of area **PIC**

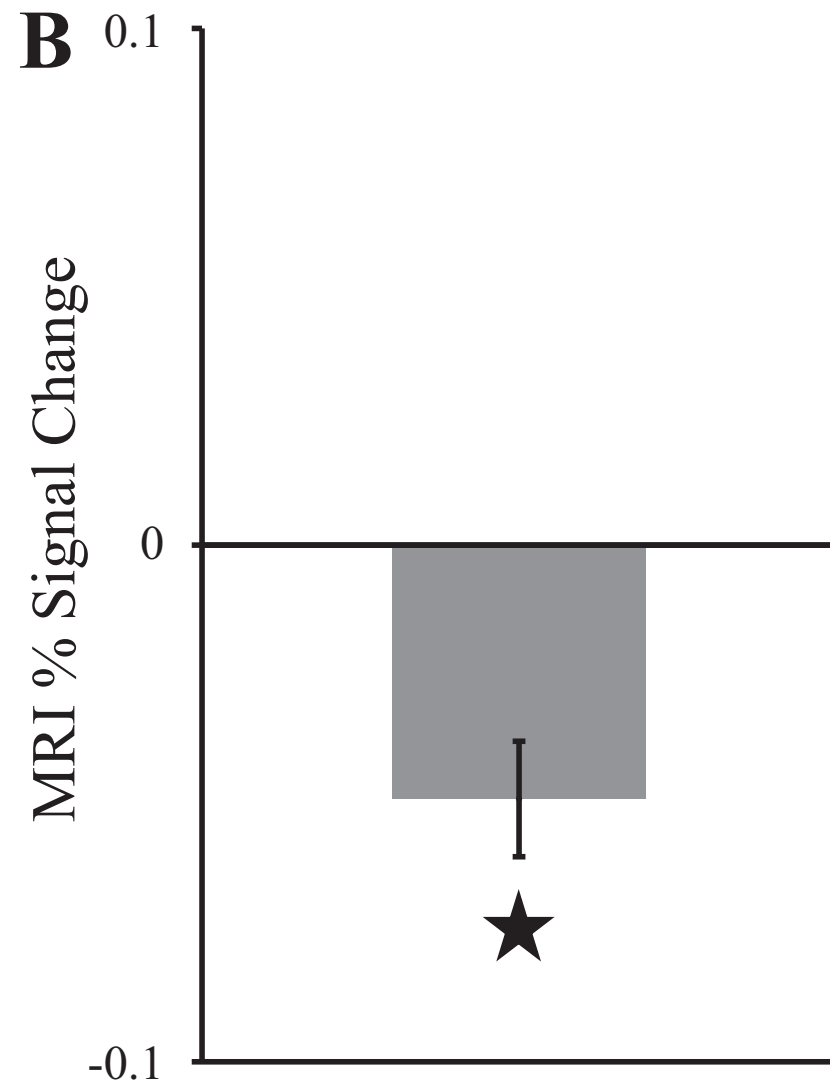
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Vestibular stimulation in humans?

### PIC with Vestibular Stimulation

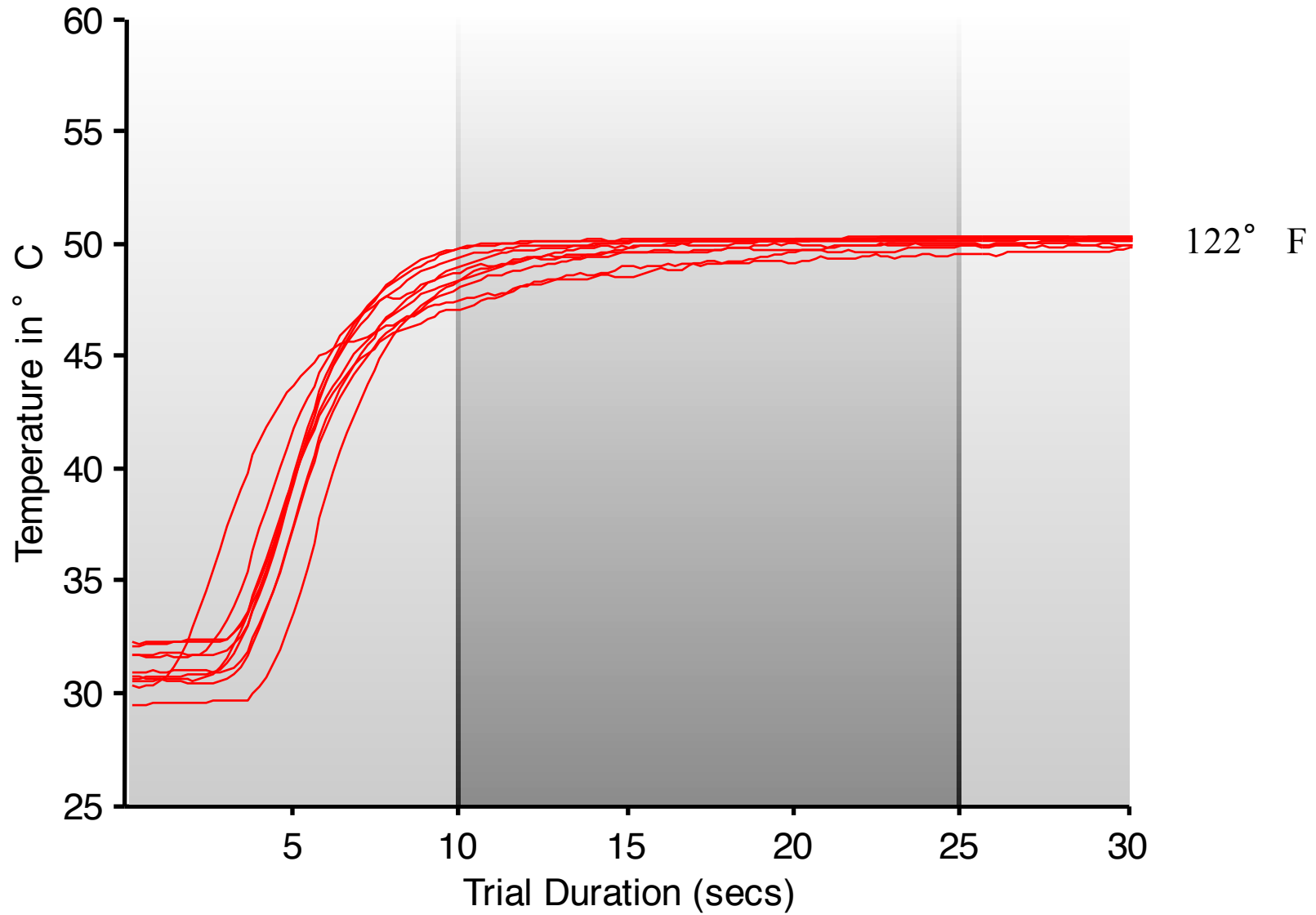


### PIVC with Visual Object Motion

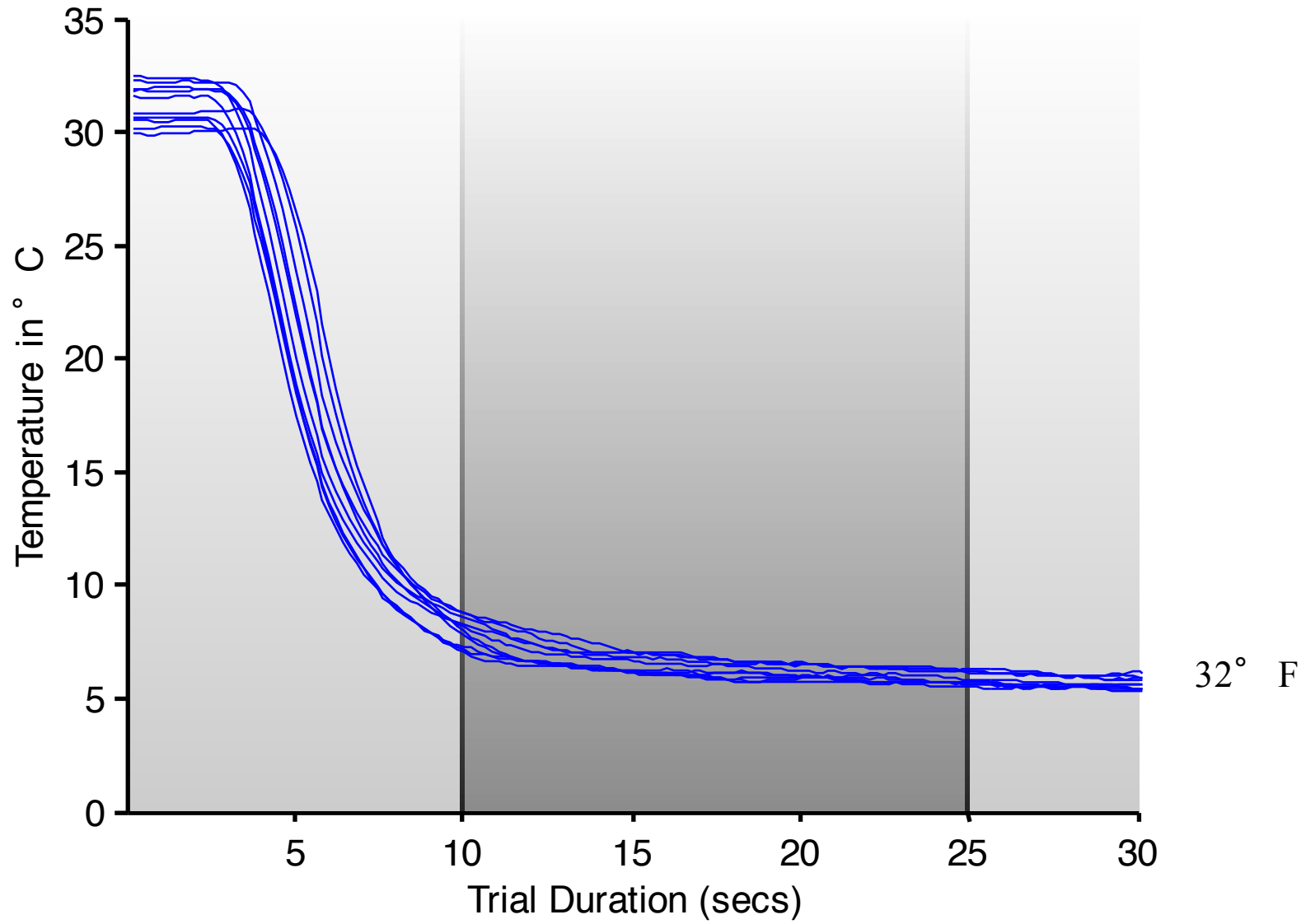




# Hot

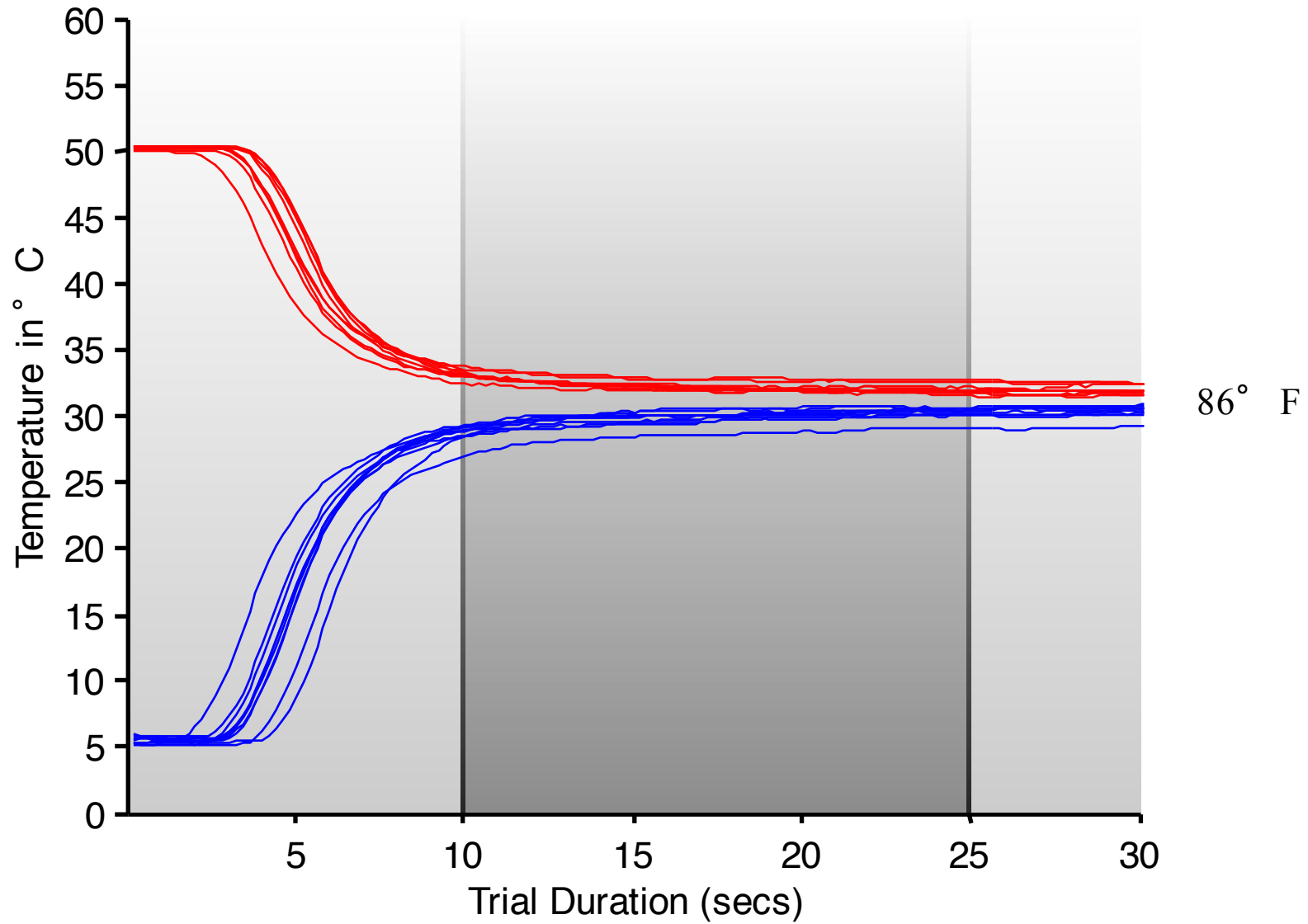


# Cold



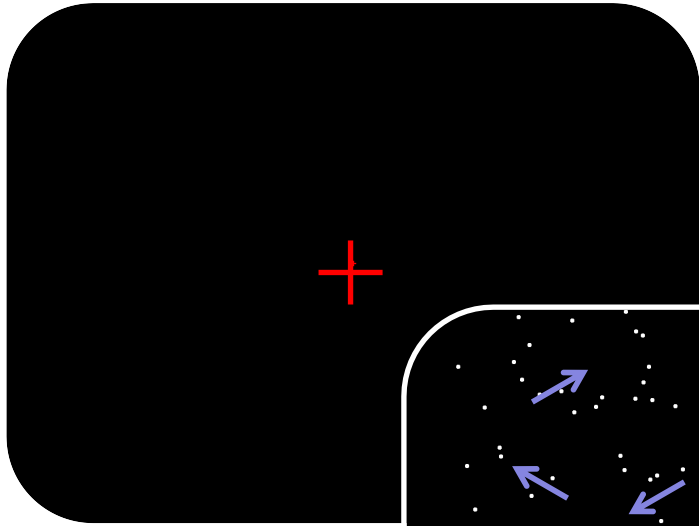


# Baseline (Warm)

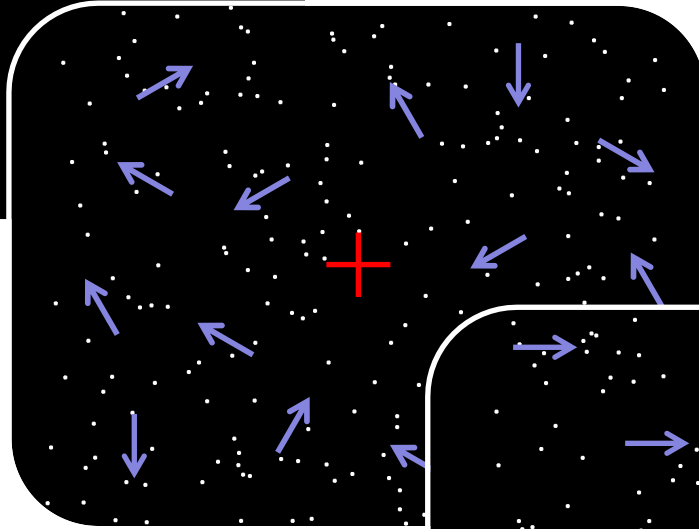


# Visual-Vestibular

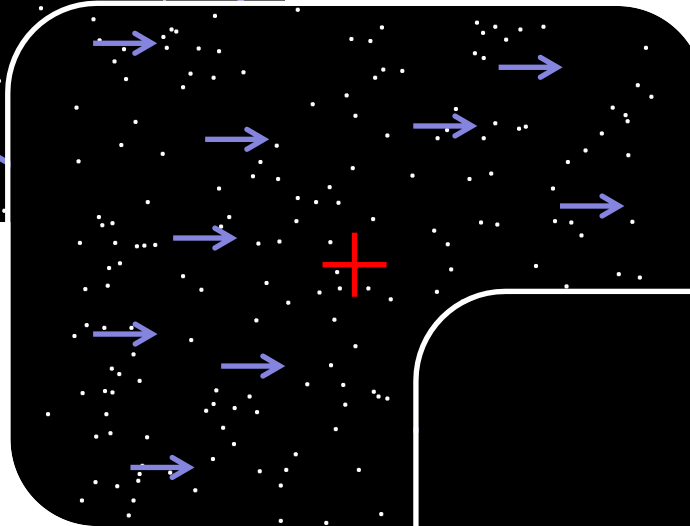
0.5 – 1 sec



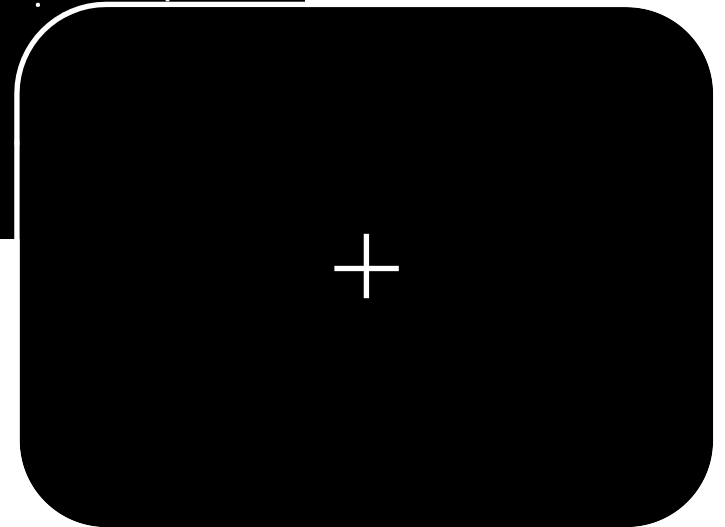
10 sec



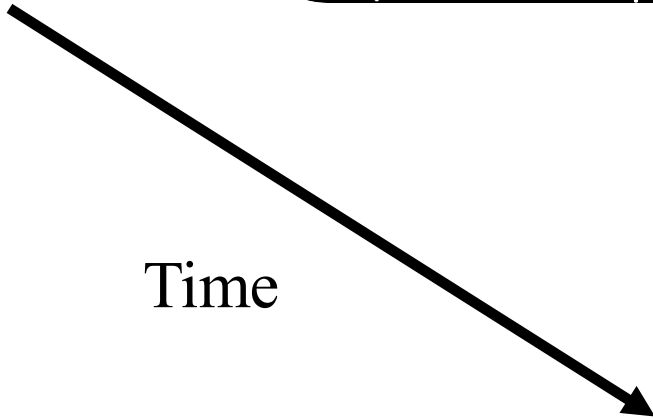
15 sec

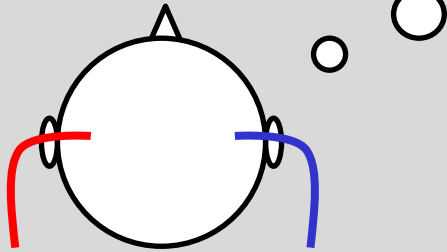
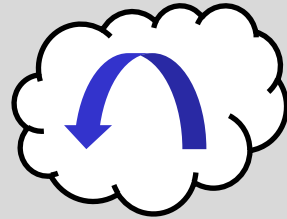
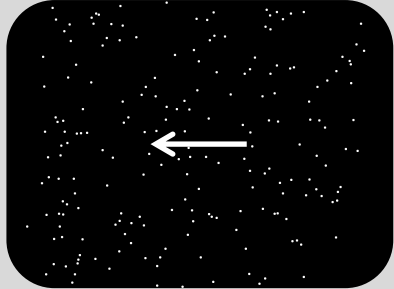


5 sec

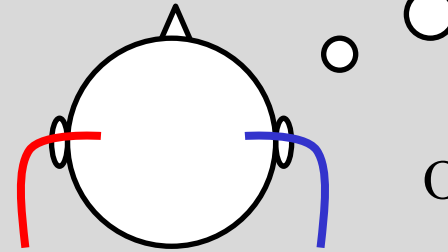
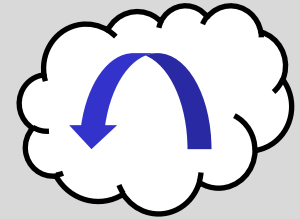
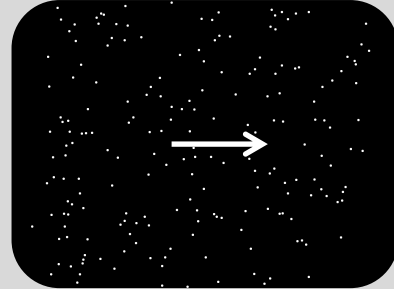


Time

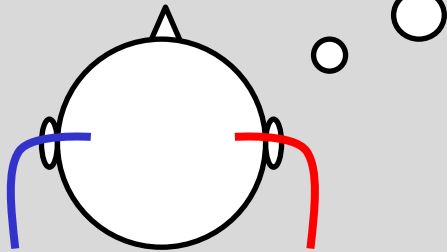
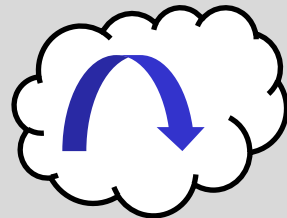
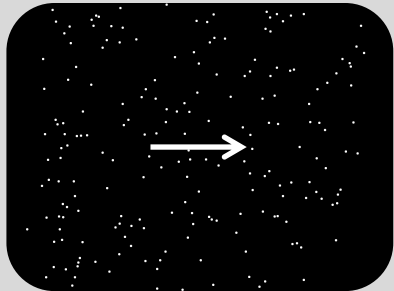




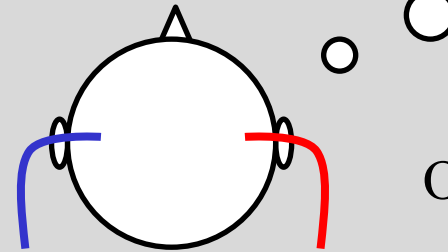
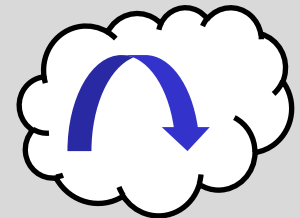
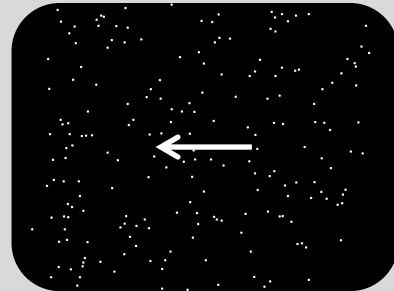
In-Phase



Out-of-Phase



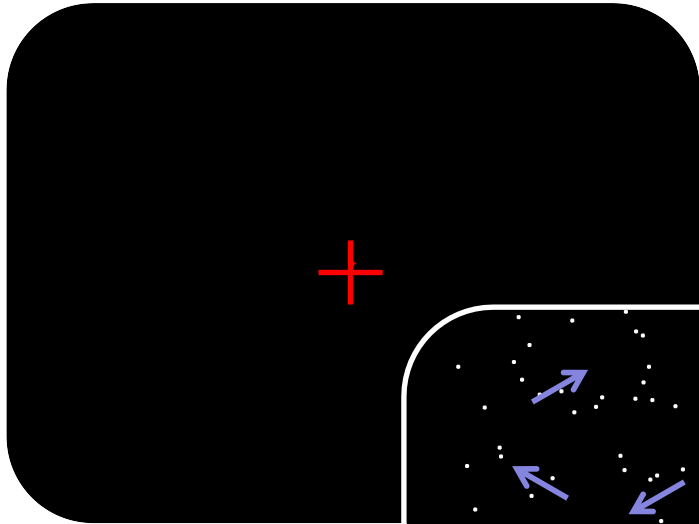
In-Phase



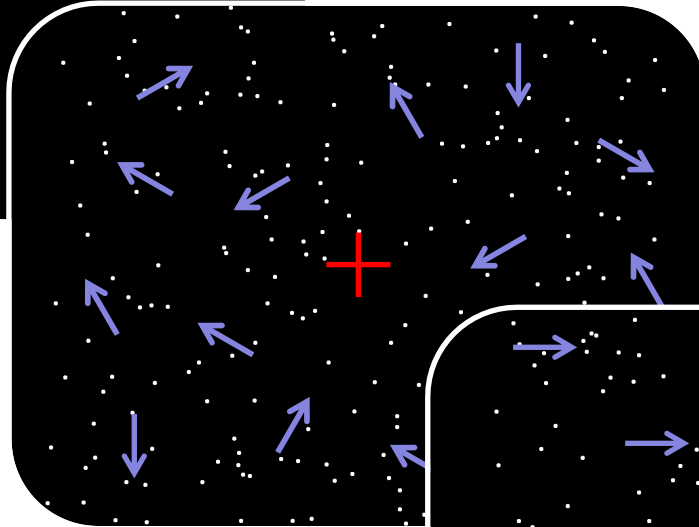
Out-of-Phase

# Visual-Vestibular

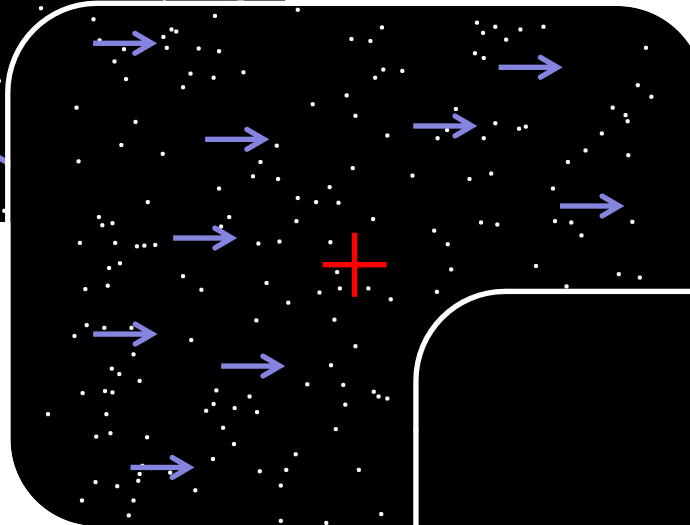
0.5 – 1 sec



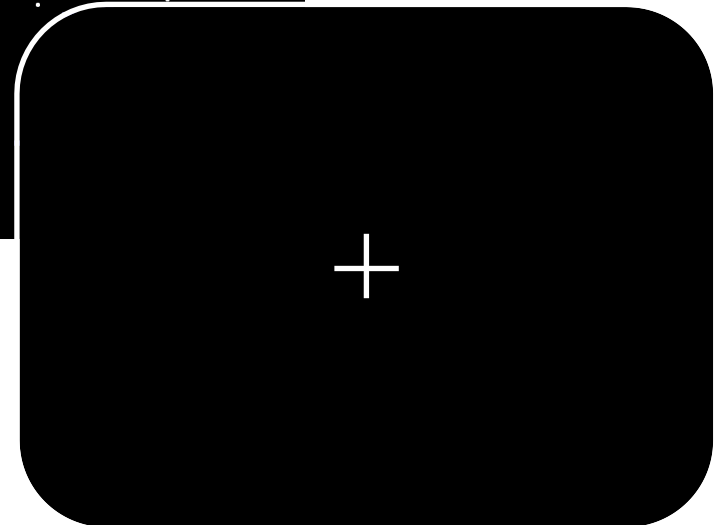
10 sec



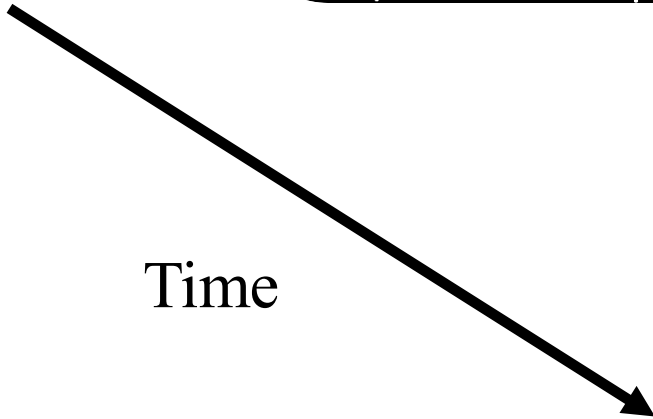
15 sec



5 sec

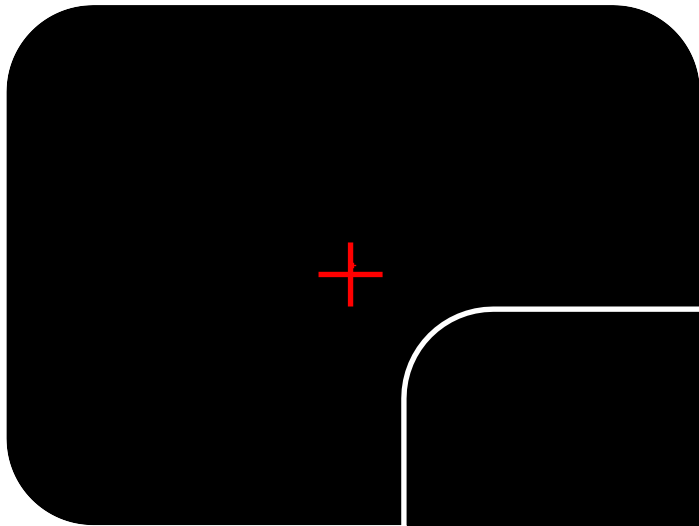


Time

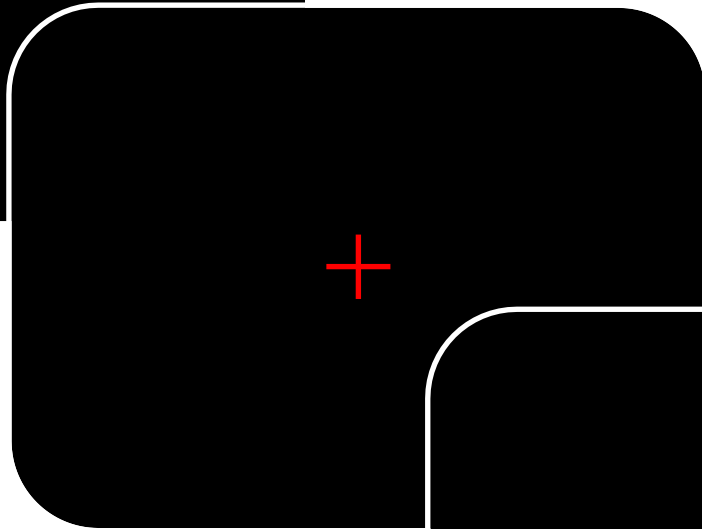


# Vestibular

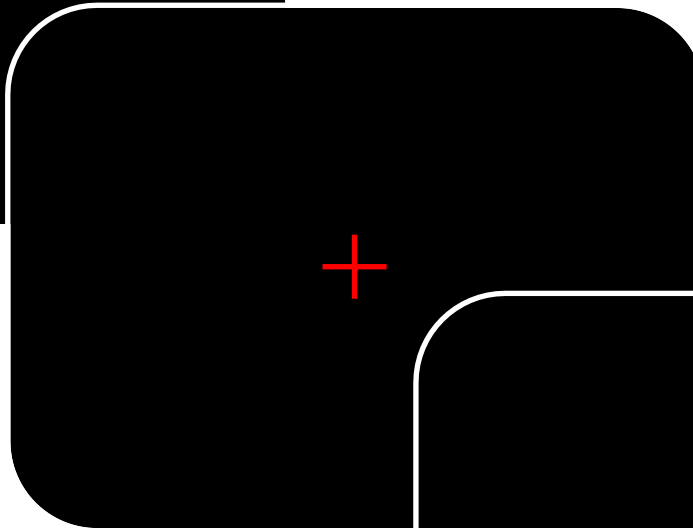
0.5 – 1 sec



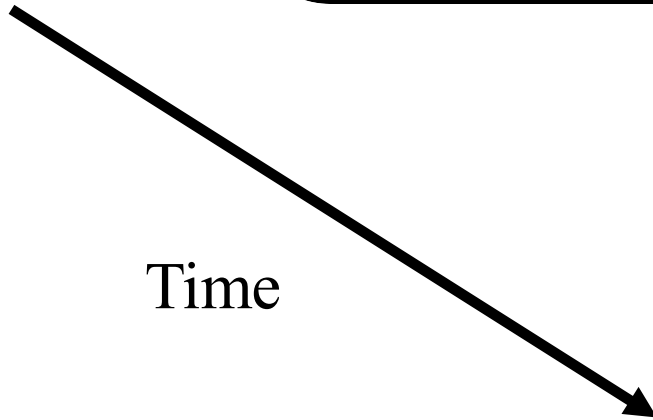
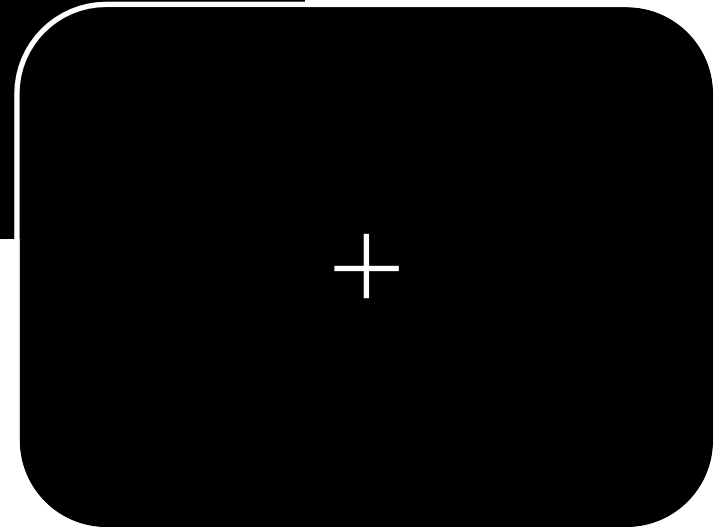
10 sec



15 sec



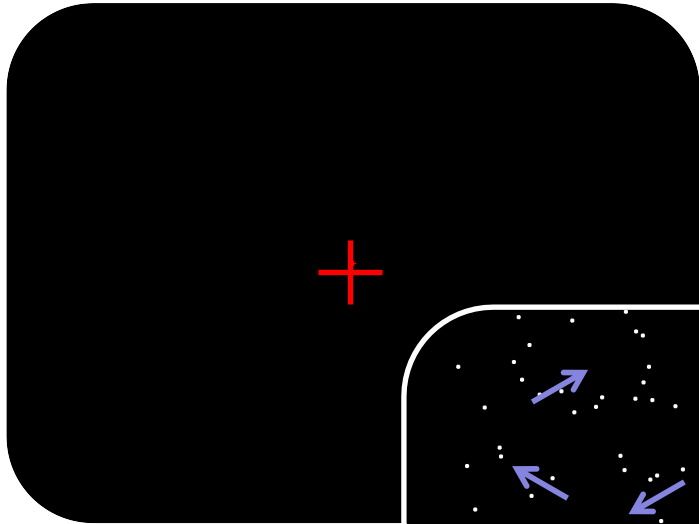
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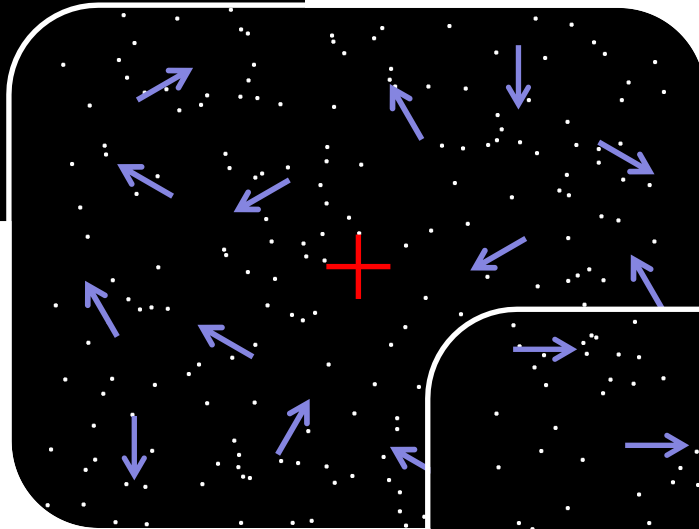
Time

# Visual- Temperature

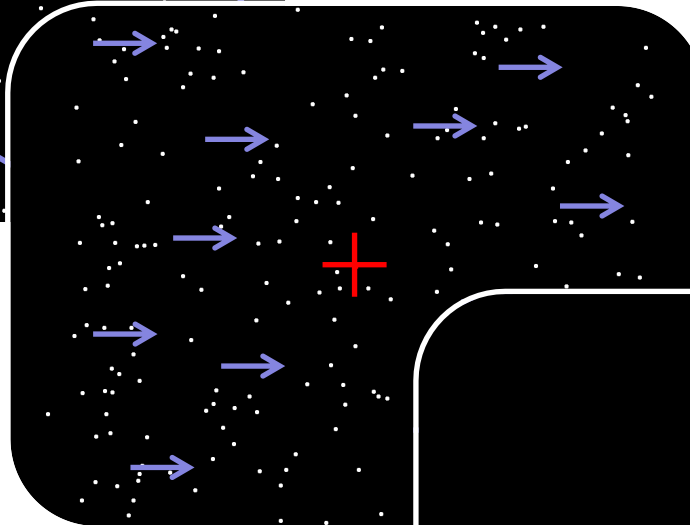
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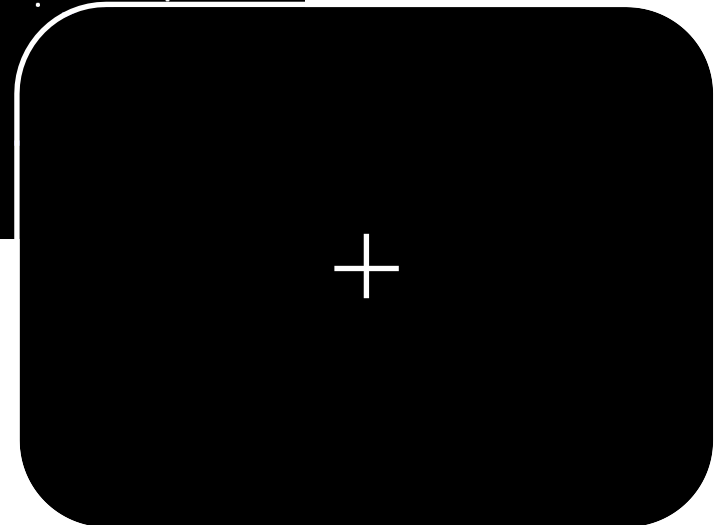
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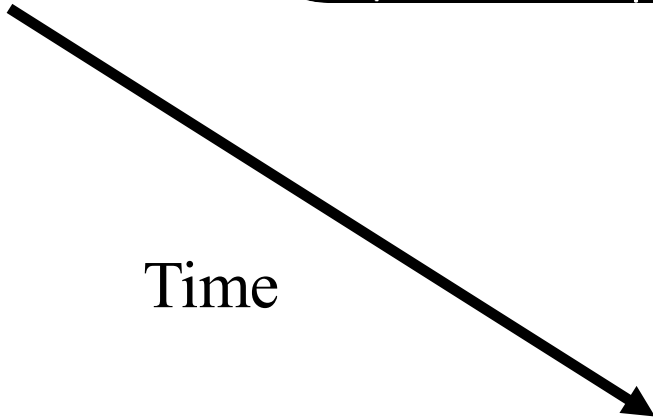
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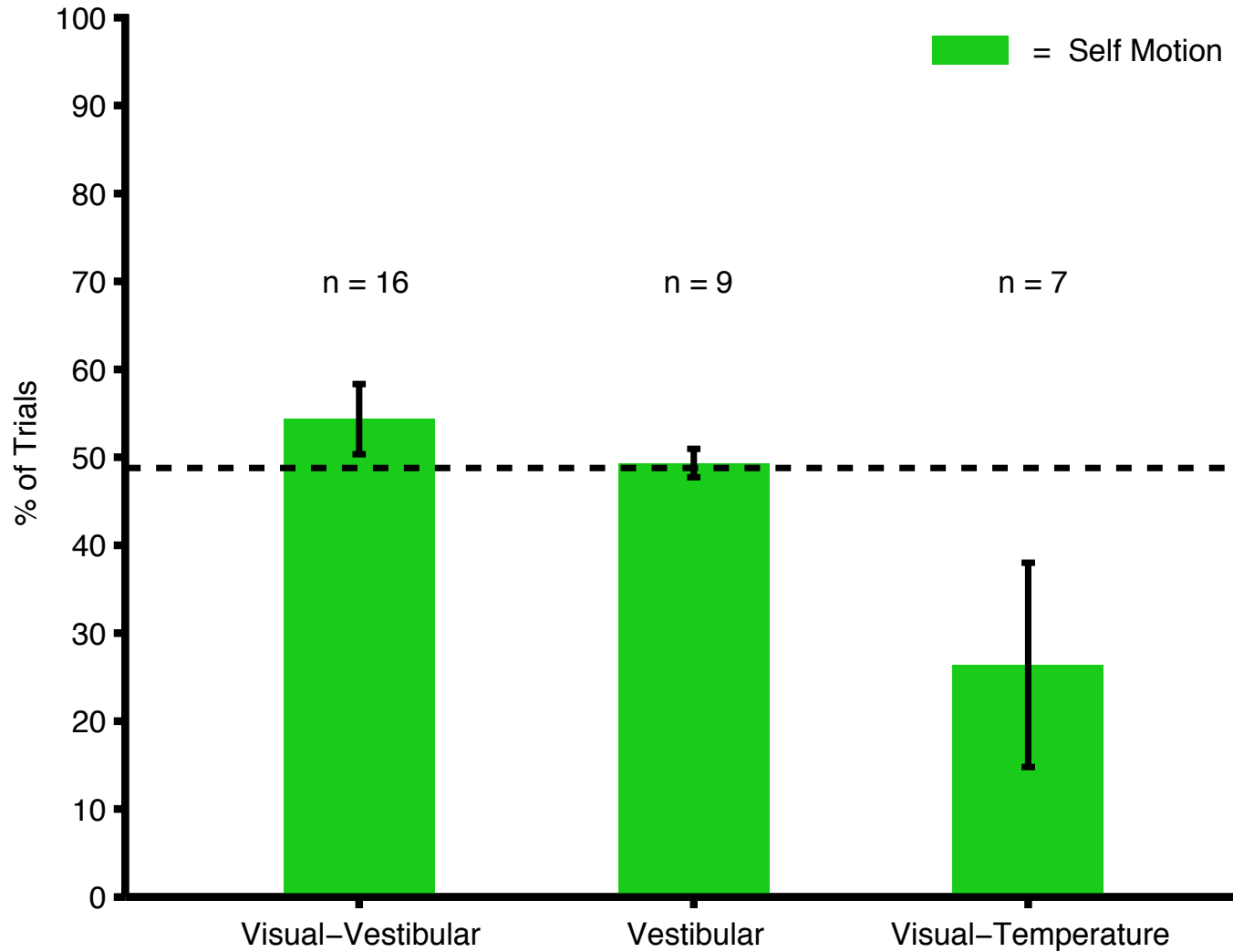
5 sec



Time



# Behavioral Results



# Functional Sessions

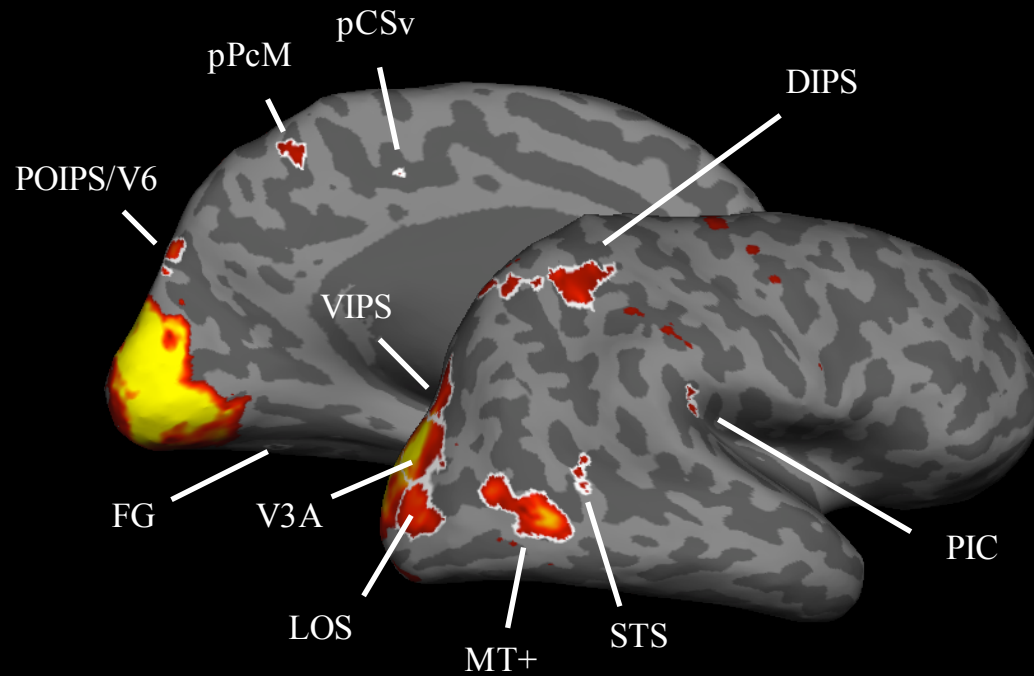
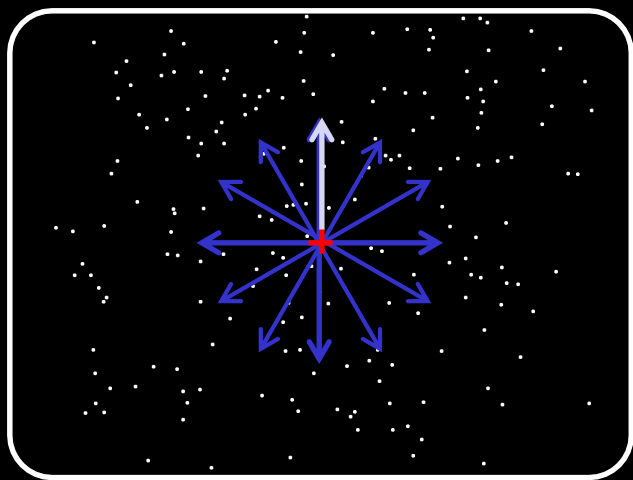
- Localizer: Motion-Cortex
- Localizer: Vestibular Cortex
- Visual-Vestibular Stimulation
- Visual-Temperature Control

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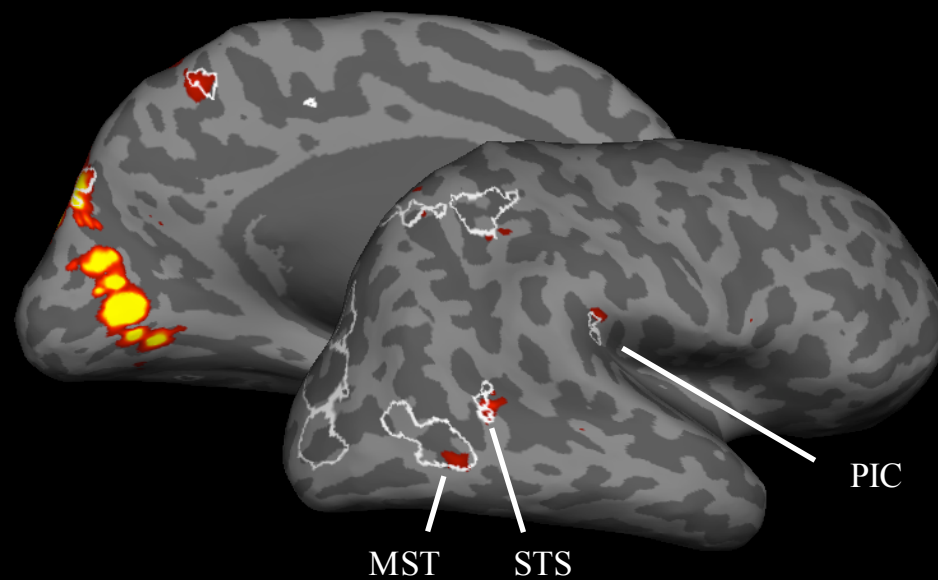
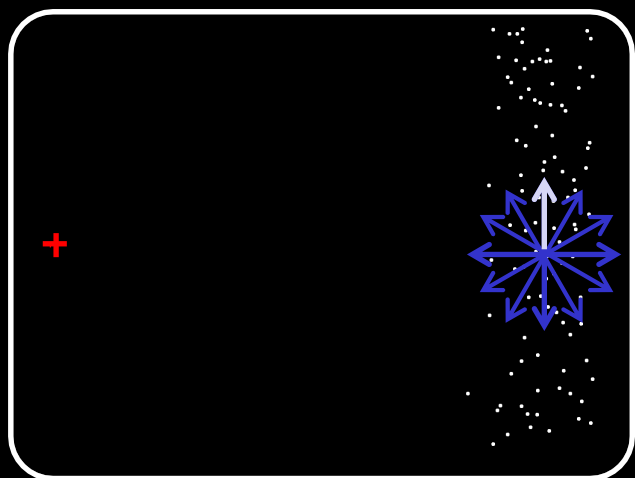
Localizer: Motion-Cortex



# a) Bilateral MT+



# b) Right MST



# Go8



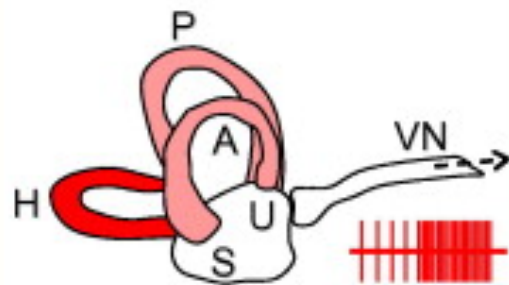
# Vestibular System

- Acceleration and position in space
- Balance
- Sense of gravity
- Self-motion
- Spatial navigation, learning, memory

## A caloric vestibular stimulation (CVS)



Injection of cold (0,4,10,20°C) or warm (44°C) water or gas into the external auditory canal.

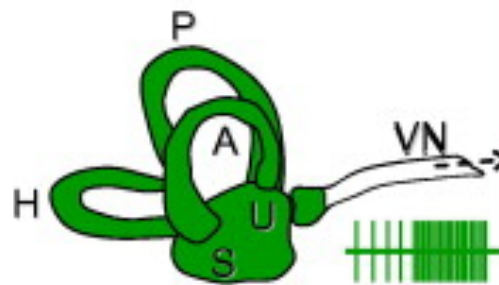


Warm water increases firing rate mainly in the afferents of the horizontal semicircular canals. A weaker contribution of vertical canals and an interaction with the neural processing of otolithic signals have been demonstrated.

## B galvanic vestibular stimulation (GVS)



Application of a percutaneous current through an anode and a cathode placed on the opposite mastoid processes.

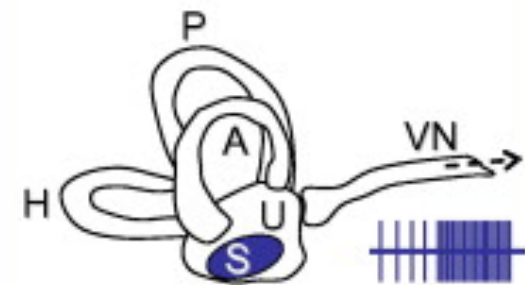


Firing rate increases in the vestibular afferents ipsilateral to the cathode and decreases to the side of the anode.

## C sound-induced vestibular stimulation

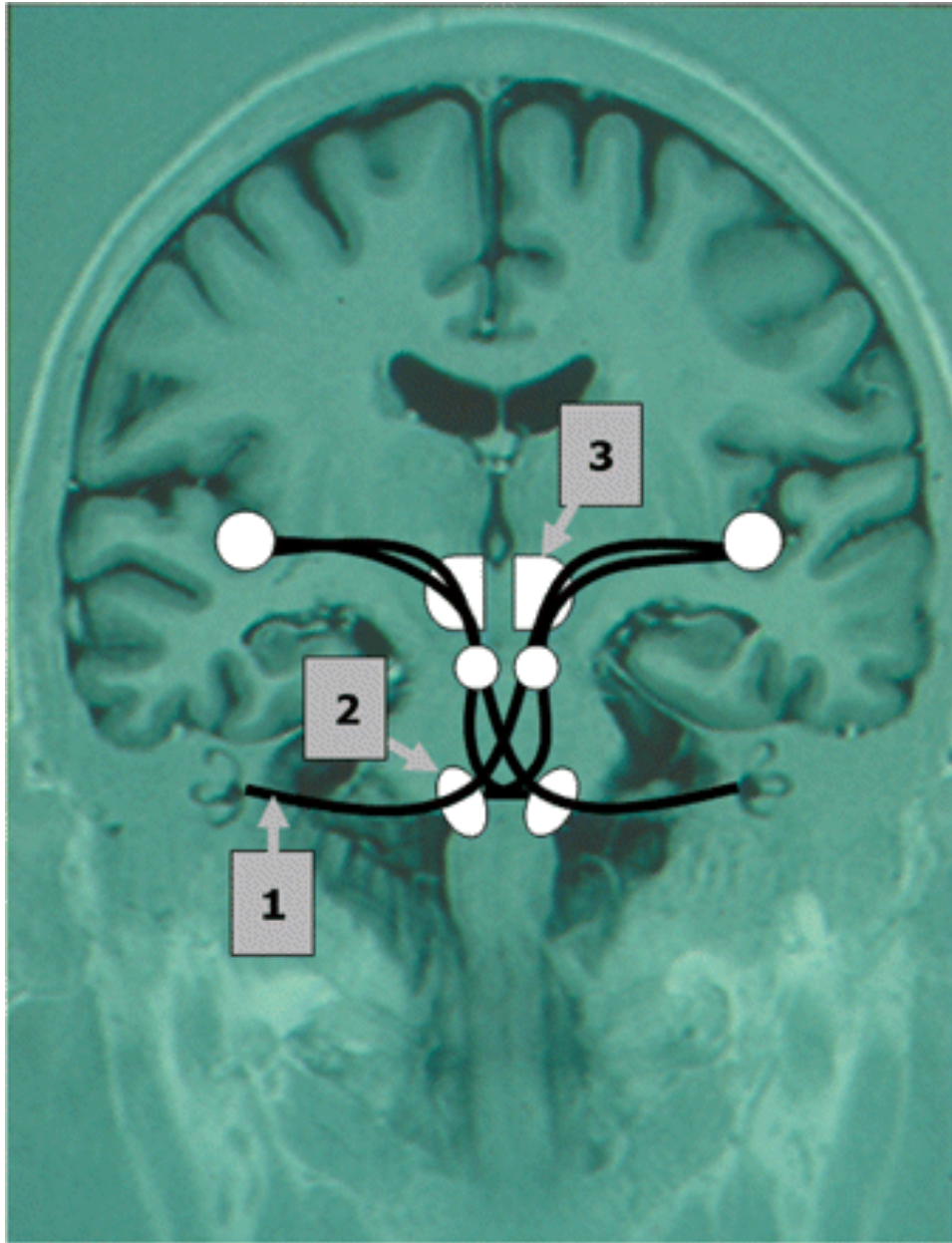


Presentation of 102 dB clicks (1 ms long, at 1 Hz) or short tone bursts (10 ms long, 500 Hz, at 3 Hz) through headphones.



Air-conducted sounds preferentially activate saccular receptors. A weaker contribution of other otolithic receptors and semicircular canals has also been proposed.

# Vestibular System



Dieterich & Brandt 2008 Brain

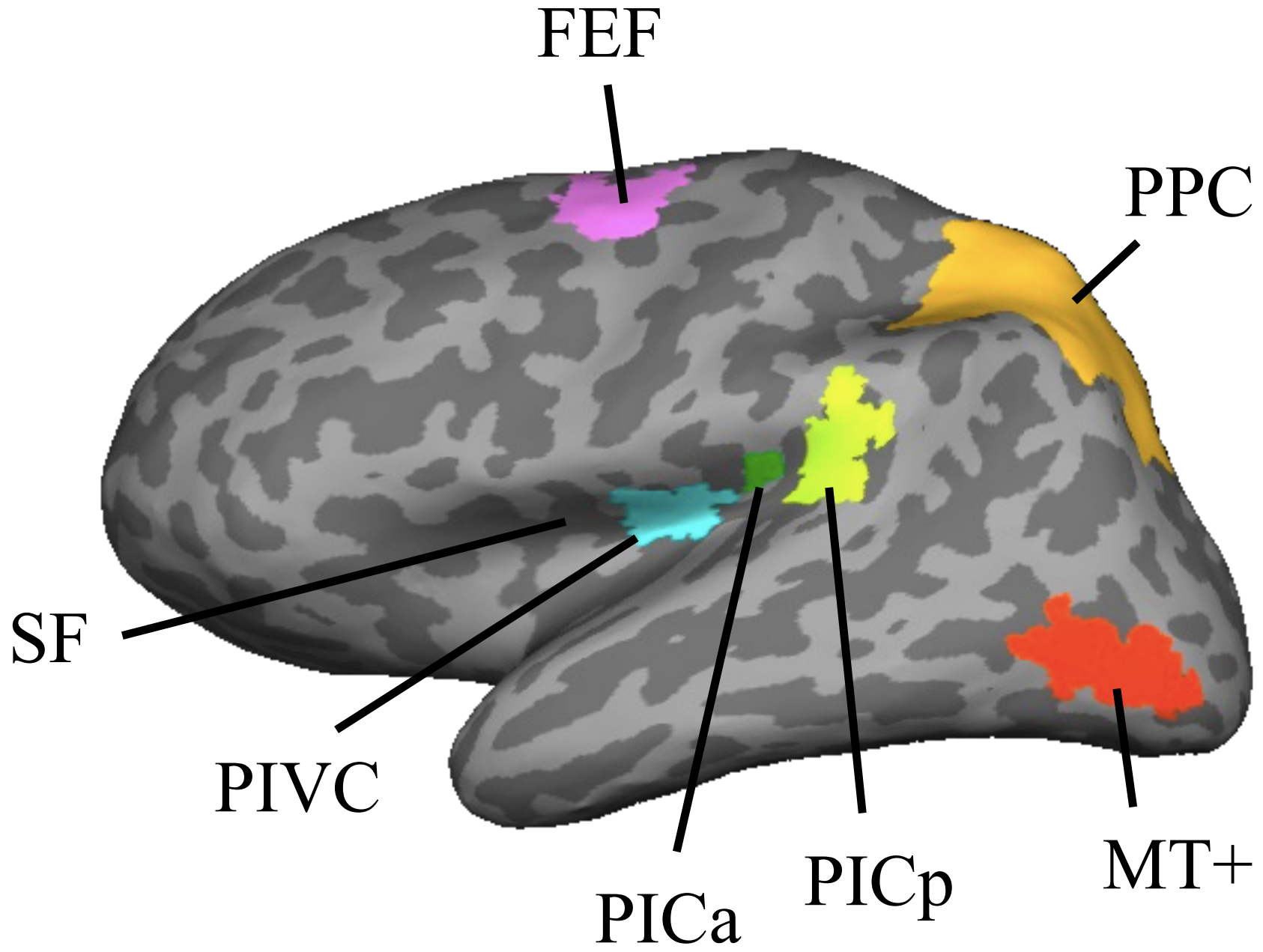
## Vestibular Pathway

- Vestibular Sensors
- Vestibular Nuclei
- Ocular Motion Nuclei
- Posterolateral Thalamus
- Cortex

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**Cortical representation** of  
vestibular input?

# Caloric Stimulation Conditions



FEF

PPC

SF

PIVC

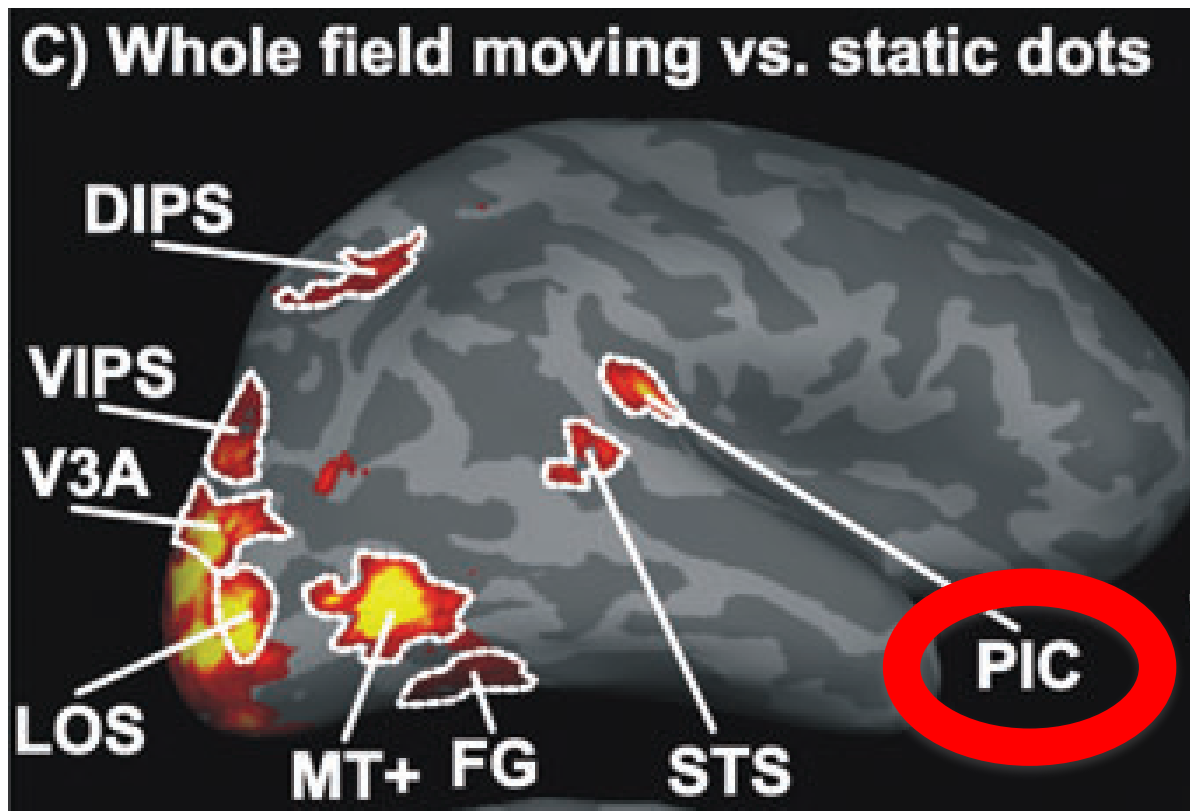
PICa

PICp

MT+

# Evidence for a Human VPS ?

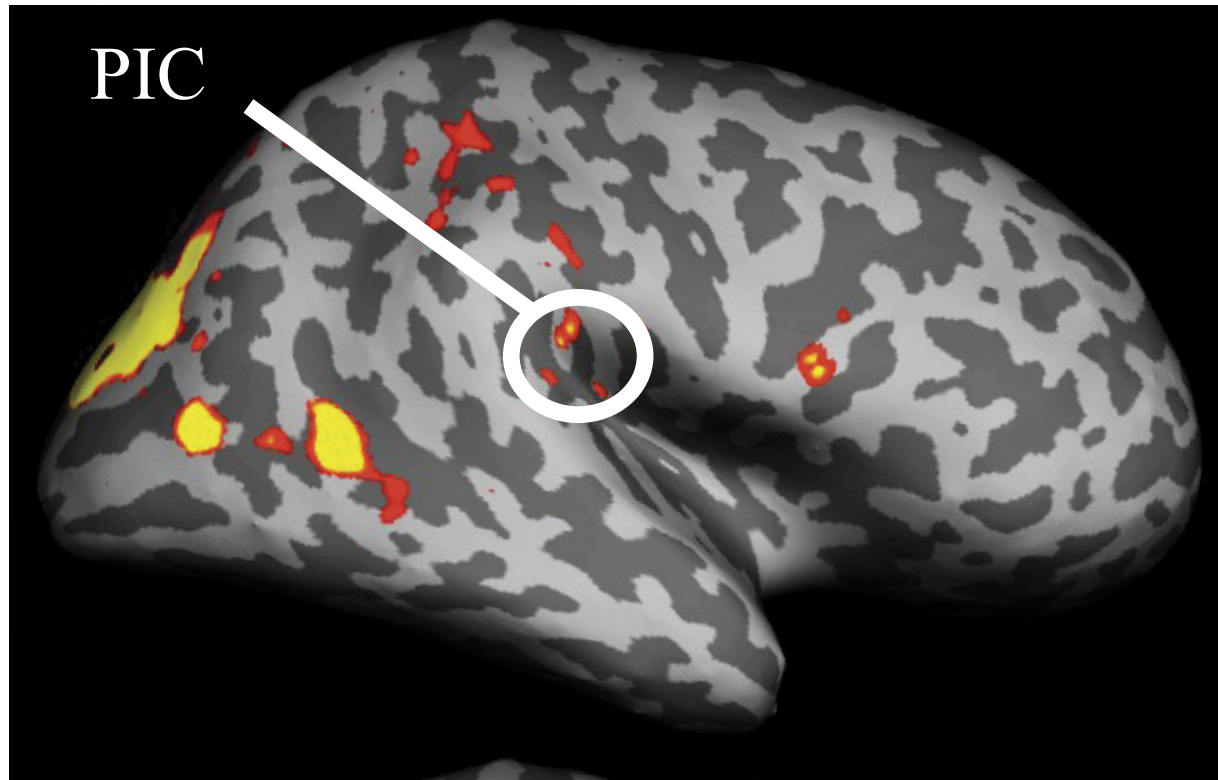
- PIC (posterior insula cortex)



Beer et al.  
2009 ESN

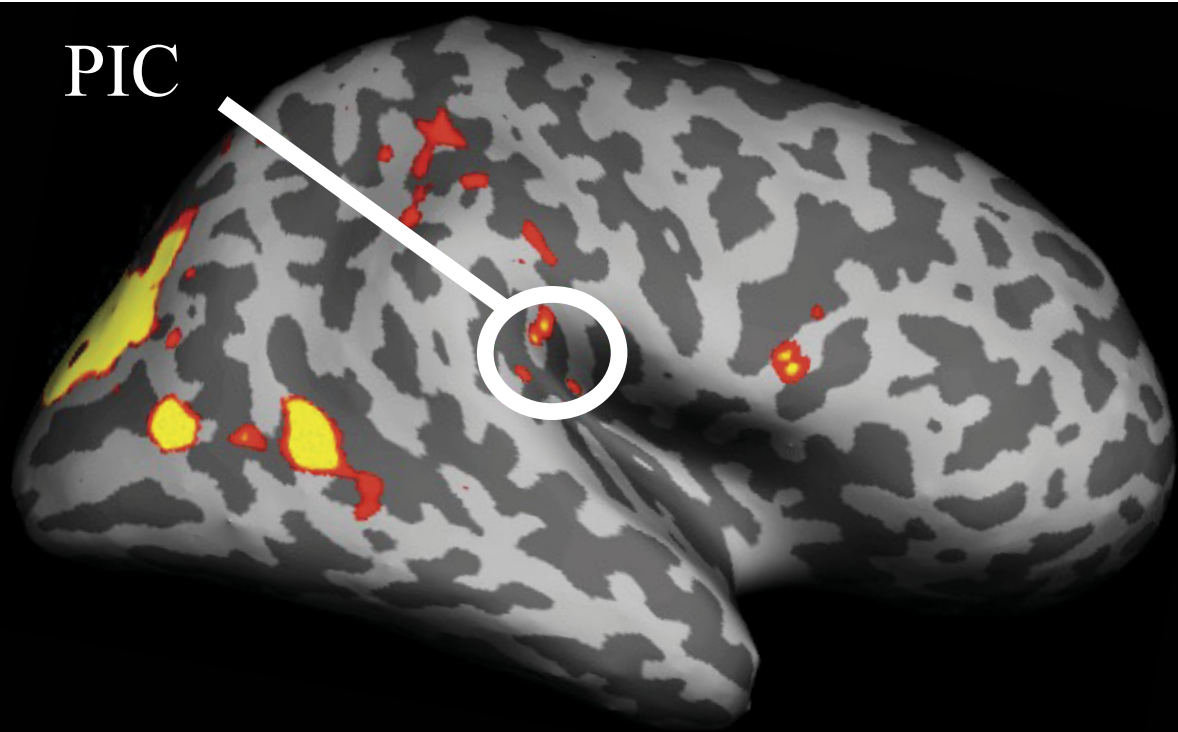


Visual

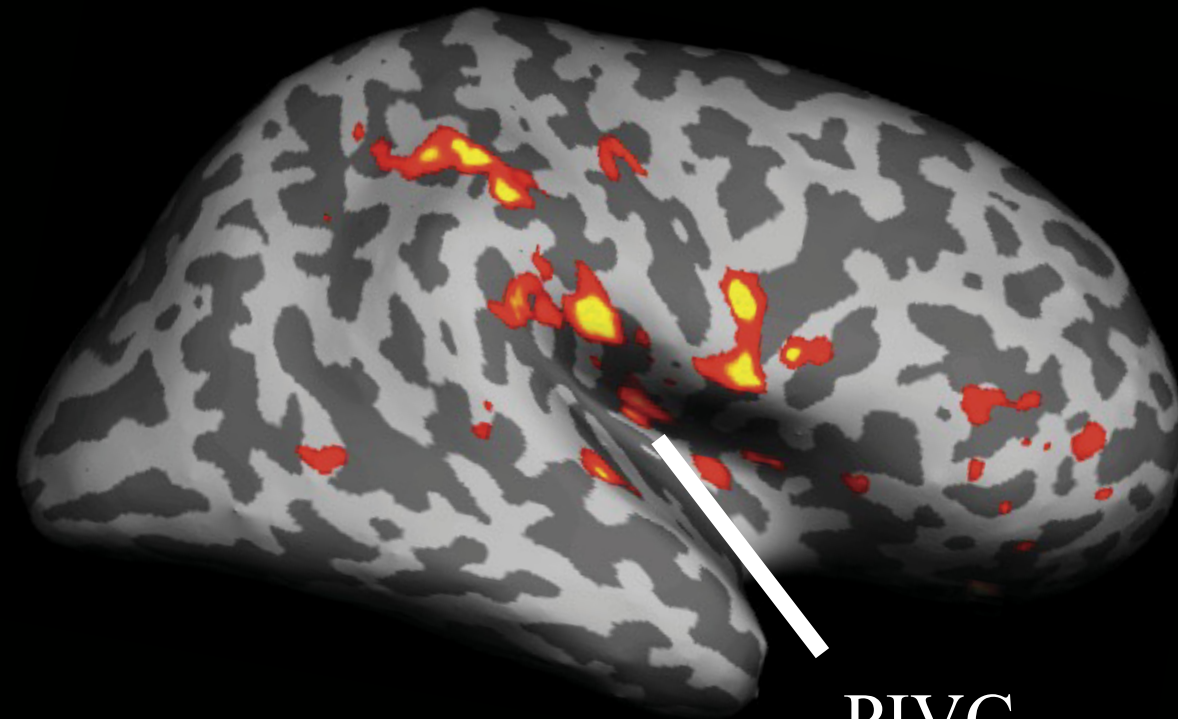


PIC

Visual



Vestibular



PIVC

# DFG-funded Projects

1. Inhibition of the vestibular system by visual attention
2. Biochemical effects of inhibition by visual attention

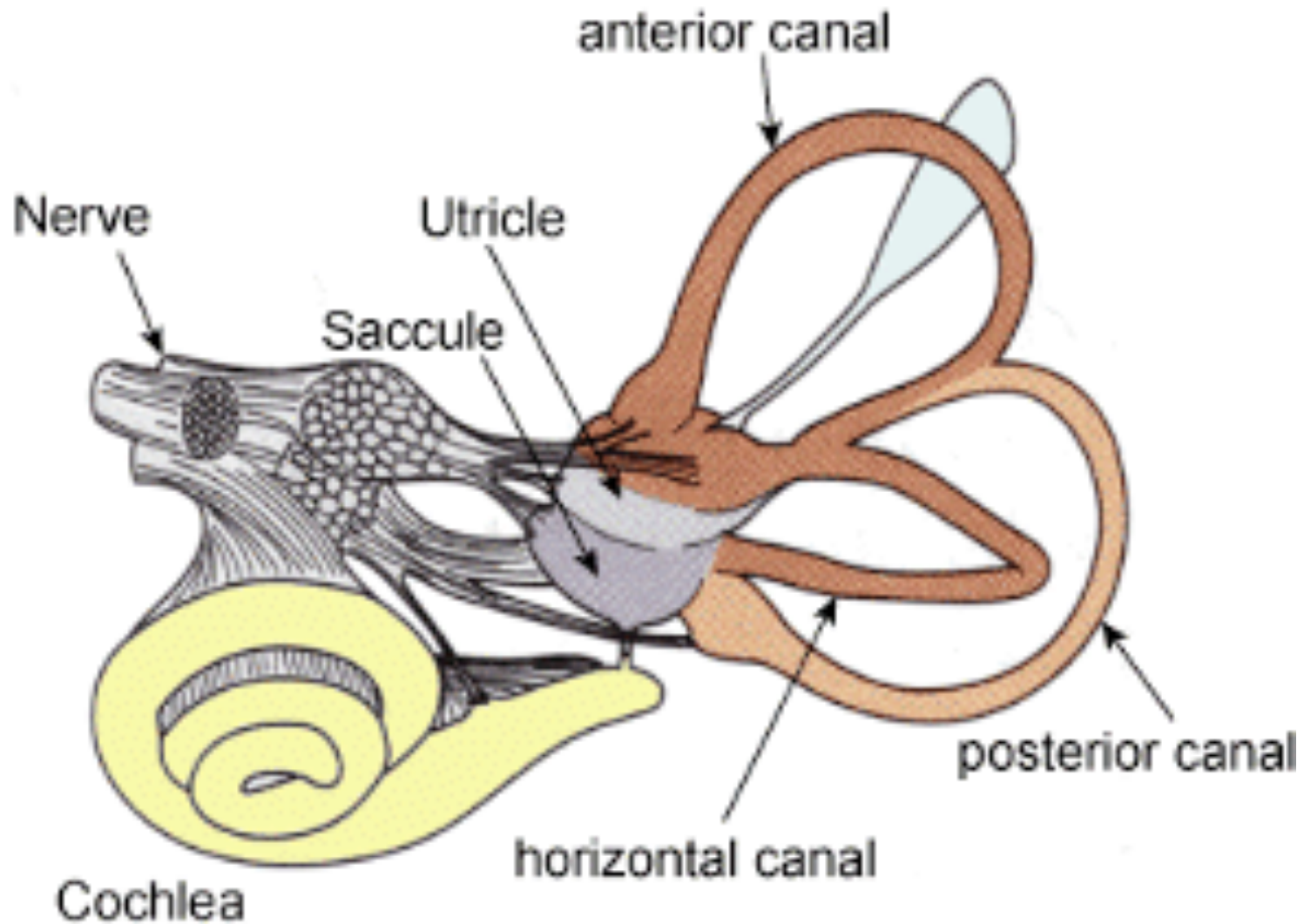
# DFG-funded Projects

1. Inhibition of the vestibular system by visual attention
2. Biochemical effects of inhibition by visual attention

# Vestibular System



# Vestibular System



# Vestibular System

