Virtual Reality and Neuroimaging to Investigate the Neuronal Process while Walking

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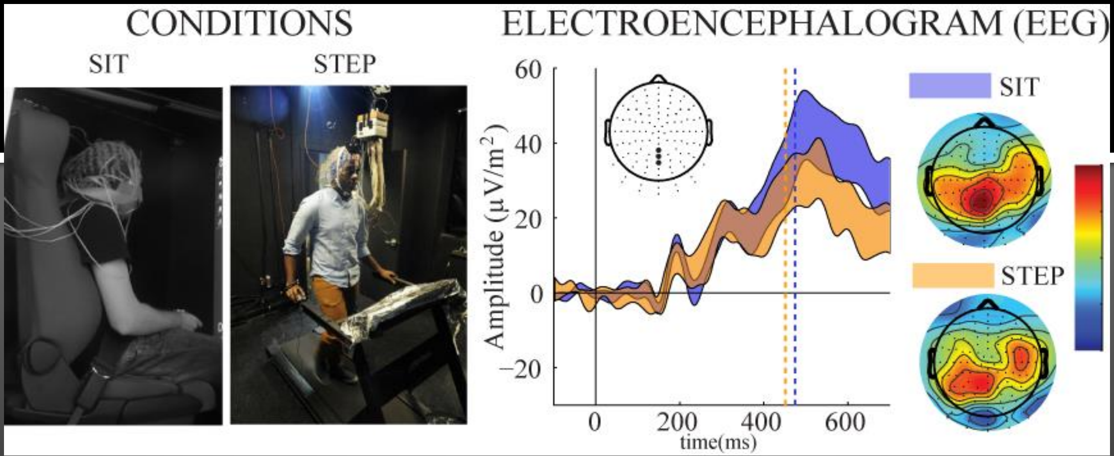
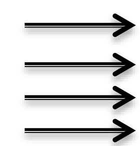
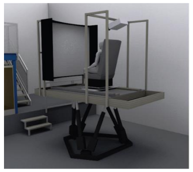


My background

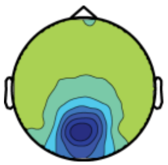
- Numerical Analysis (Trinity College Dublin, PhD work)
  - Robust Numerical methods of Prandtl Boundary Layer Problems



- Self-motion Perception (Max Planck Institute for Biological Cybernetics)
  - Walking
  - Driving



- Unisensory and Multisensory processing
  - Developmental Disorders (Albert Einstein College of Medicine)
    - Autism Spectrum Disorder, Niemann Pick Type C
  - Movement Disorders (Trinity Centre for Bioengineering)
    - Parkinson's Disease
    - Dystonia



Talk Overview

1. Introduction
2. Distance Perception
3. Feasibility of neural recordings while moving
4. Motor preparation in Parkinson's disease
5. Cognitive flexibility of visual load while walking

Talk Overview

1. **Introduction**
   I. **Virtual Reality**
   II. **Sensory information**

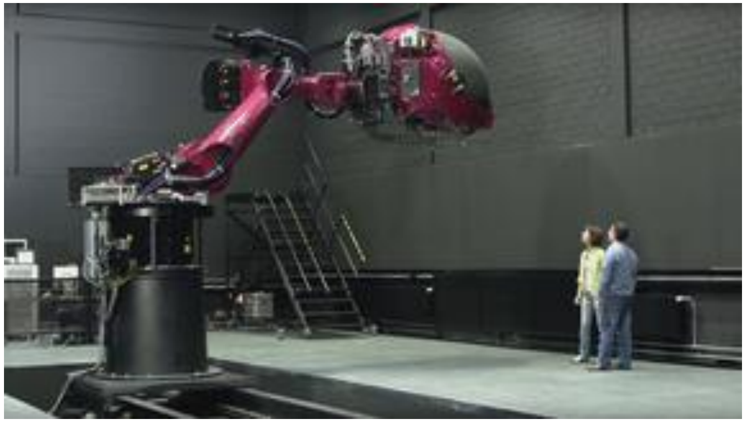
2. Distance Perception

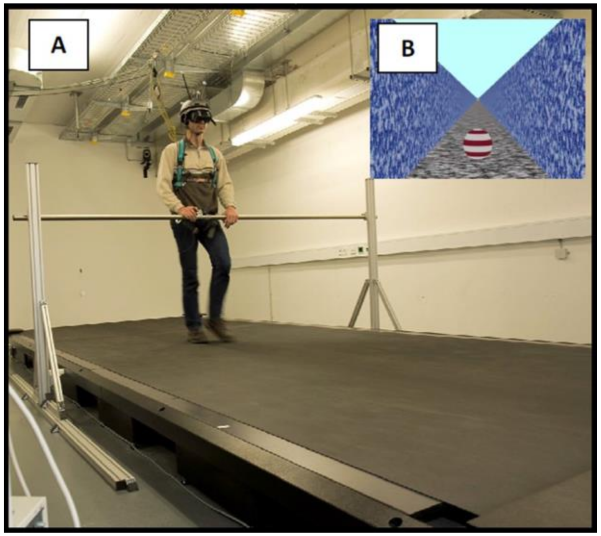
3. Feasibility of neural recordings while moving

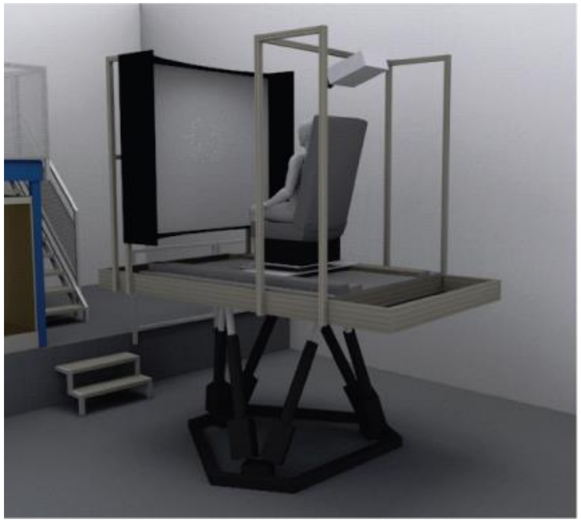
4. Motor preparation in Parkinson's disease

5. Cognitive flexibility of visual load while walking

Virtual Reality

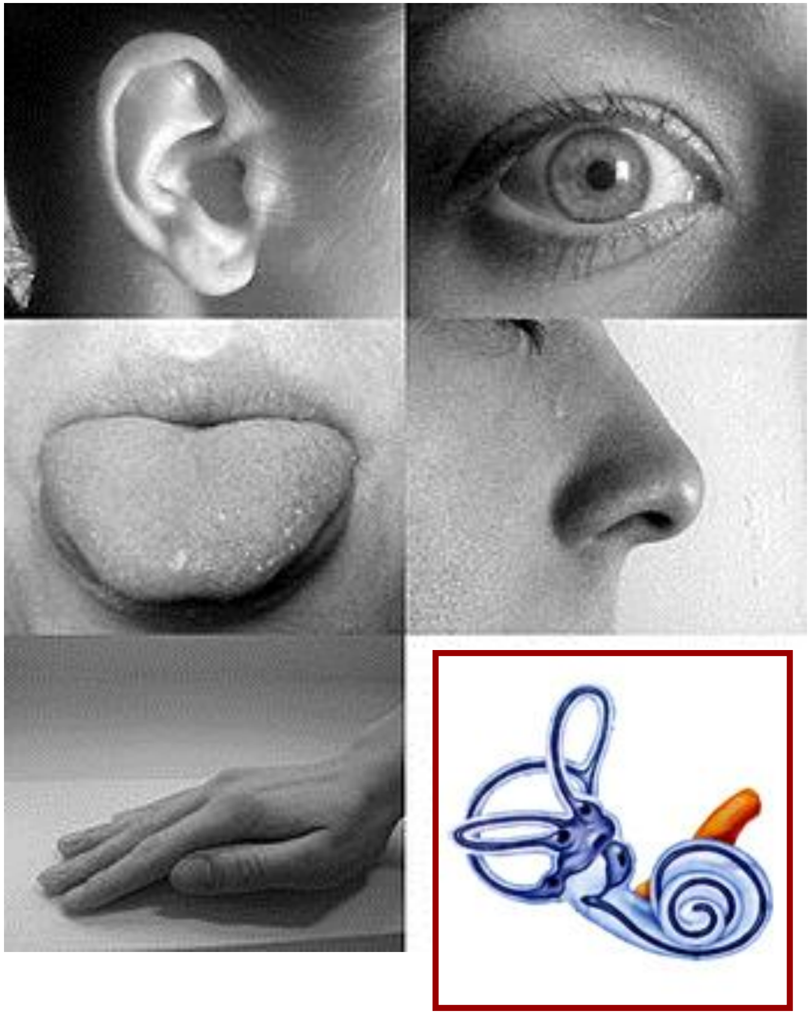






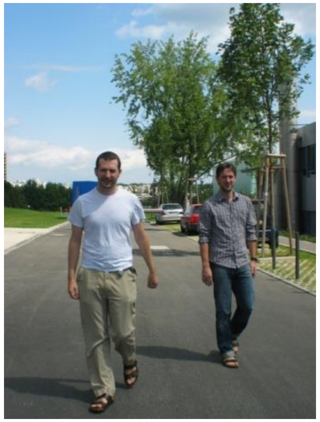
Sensory information

- Hearing
- Sight
- Taste
- Smell
- Touch
- Vestibular
- Proprioception



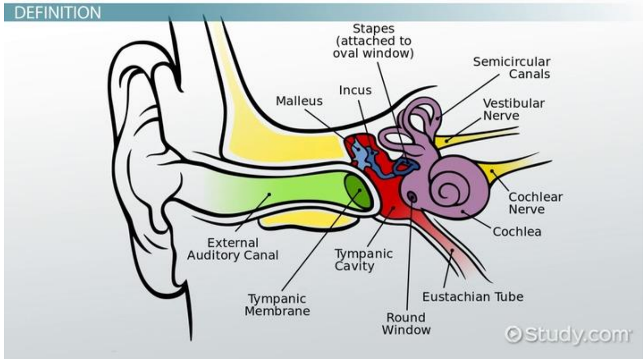
Self-motion

- Self-motion
  - Walking
  - Driving
- Cues for Self-motion
  - Visual
  - Vestibular
  - Proprioception
  - Etc.

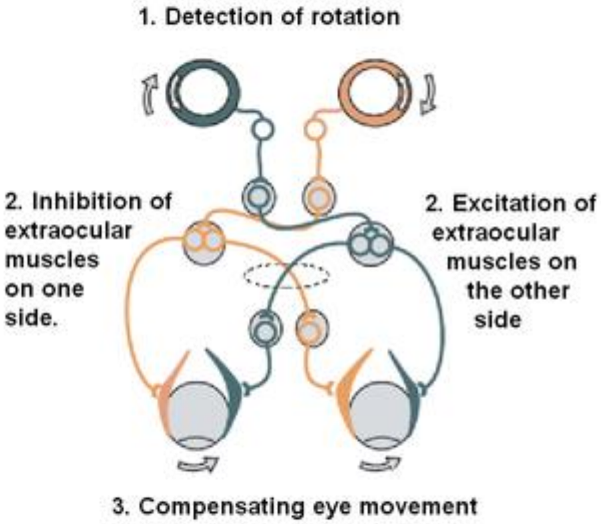


Body motion Cues

- Vestibular
  - Eye movements
  - Heading
  - Acceleration



- Proprioception
  - Somatosensory
  - Joints



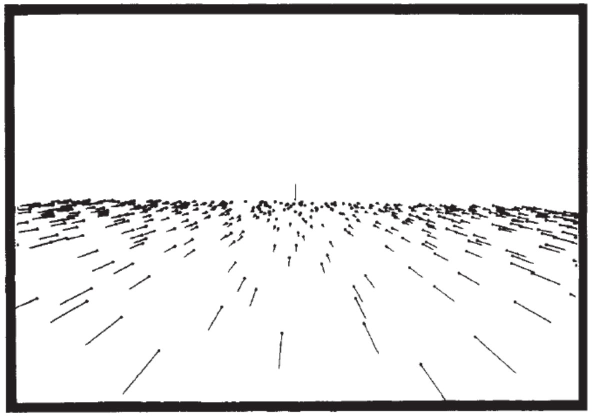
Optic flow

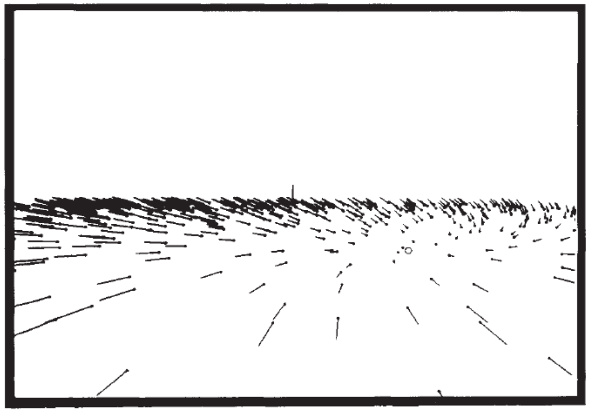
Behavioural

- Distance perception
- Heading

Neurophysiology

- Vection
  - hFMRI (MT+)
- Heading
  - MST





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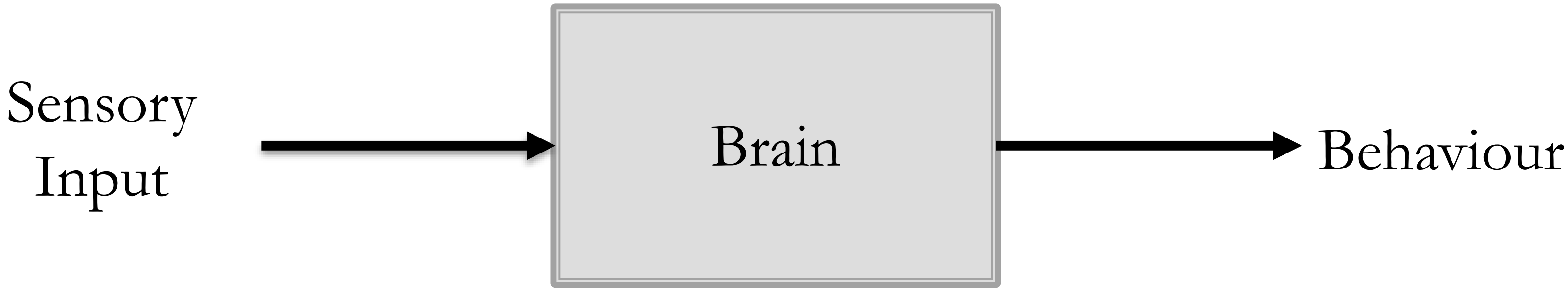
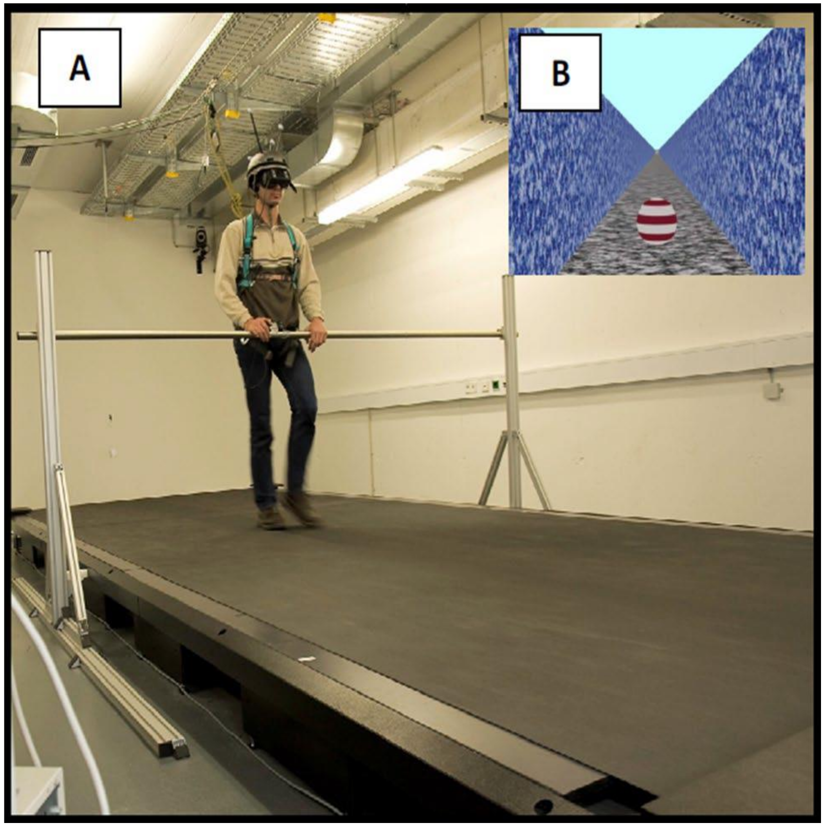
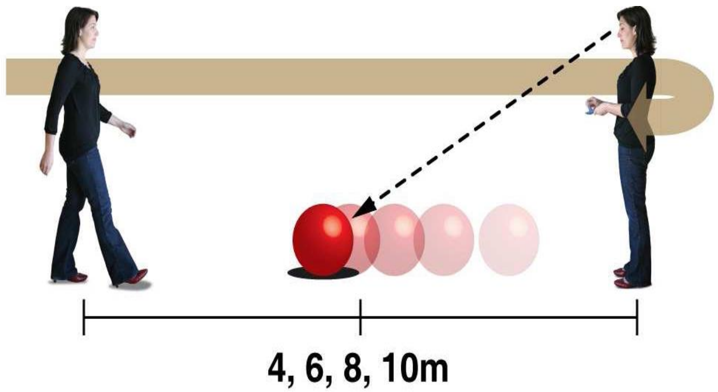
How a Mathematician starts with the Brain



The Experiment





- Visual
- Proprioception (no-vision)
- Combined
- 4m, 6m, 8m, 10m

Study 1

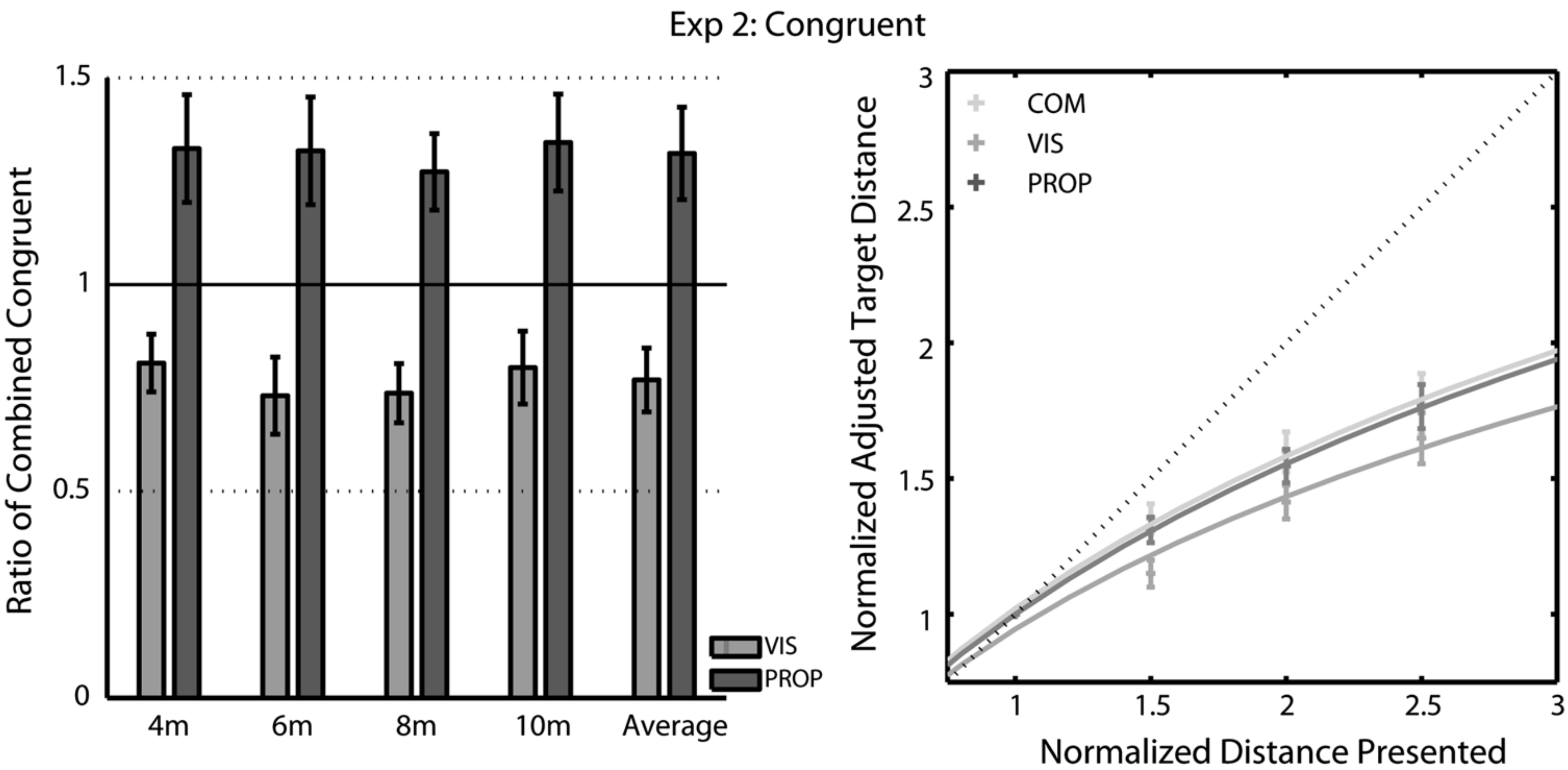
- Change the speed of the proprioceptive
- $\times\, 0.7,\ \times\, 1.4$

- Leaking Integrator
- $\frac{dp}{dx} = -\alpha p + k$

- α – leak rate
- k-sensory gain

- 20 participants

Study 1



Exp 2: Congruent
Ratio of Combined Congruent
1.5
1
0.5
0
4m
6m
8m
10m
Average
VIS
PROP
Normalized Adjusted Target Distance
3
2.5
2
1.5
1
COM
VIS
PROP
1
1.5
2
2.5
3
Normalized Distance Presented

Maximum Likelihood Estimation

$$COM = w_{VIS}VIS + w_{PROP}PROP$$

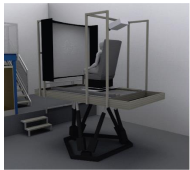
Observed

$$w_{VIS} + w_{PROP} = 1$$

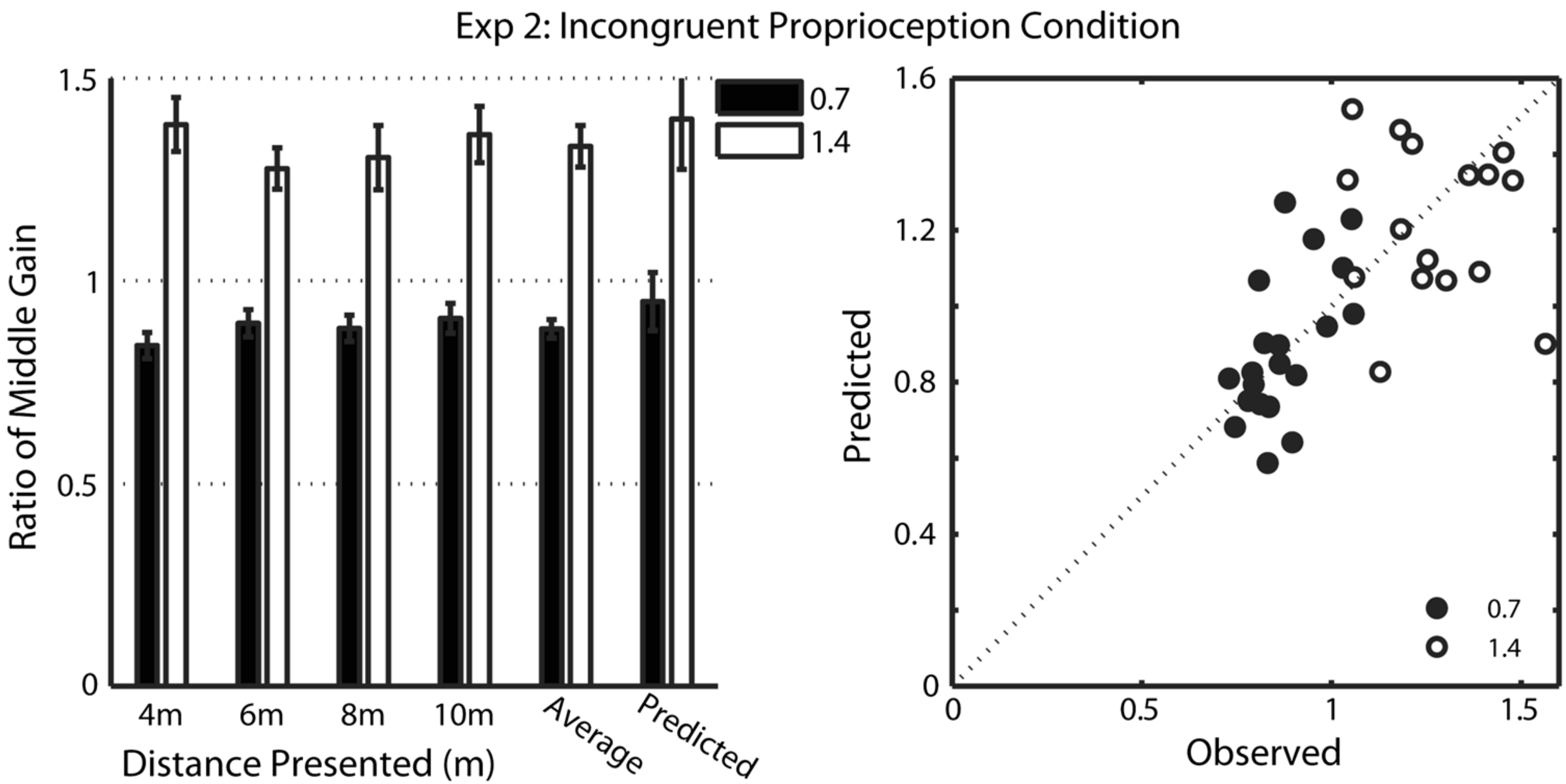
$$w_{Vis} = \frac{\mu_{COM} - \mu_{PROP}}{\mu_{Vis} - \mu_{PROP}} \qquad w_{PROP} = \frac{\mu_{COM} - \mu_{PROP}}{\mu_{Vis} - \mu_{PROP}}$$

Predicted

$$\widehat{COM}^{Gain} = w_{VIS}VIS^{Gain} + w_{PROP}PROP$$



Study 1



Exp 2: Incongruent Proprioception Condition
Ratio of Middle Gain
1.5
1
0.5
0
0.7
1.4
4m
6m
8m
10m
Average
Predicted
Distance Presented (m)
Predicted
1.6
1.2
0.8
0.4
0
0
0.5
1
1.5
Observed
0.7
1.4

Summary I

- This study supports previous findings that indicate a dominant role for body-based cues over dynamic visual flow in the estimation of travelled distances.
- The combination of visual and body based cues for walking is partially predicted by a Maximum Likelihood Estimation model

Talk Overview

1. Introduction

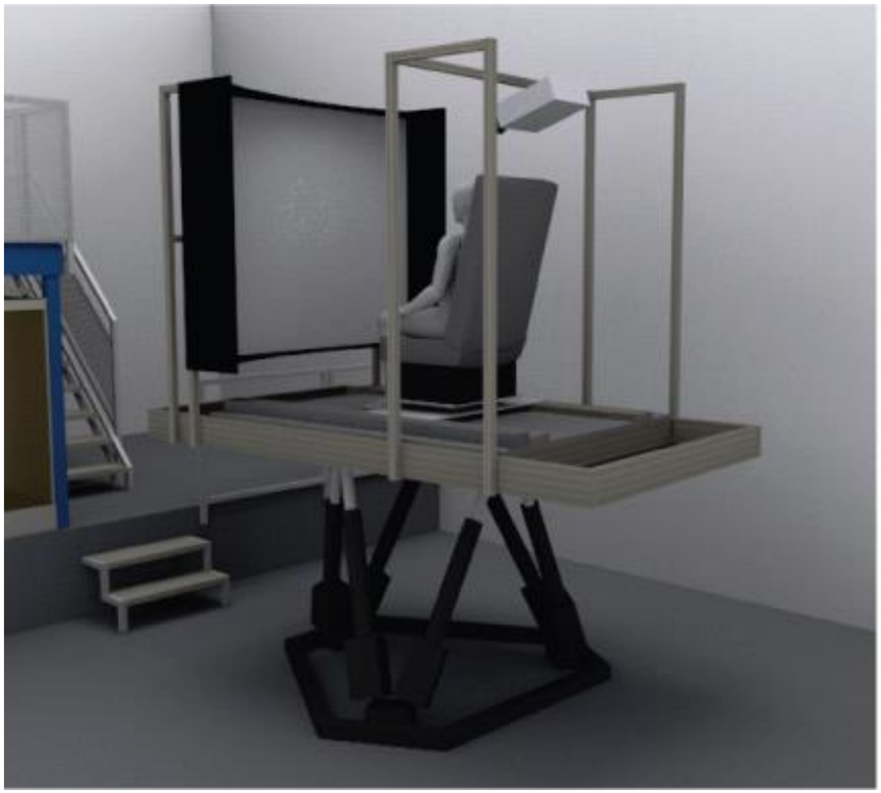
2. Distance Perception

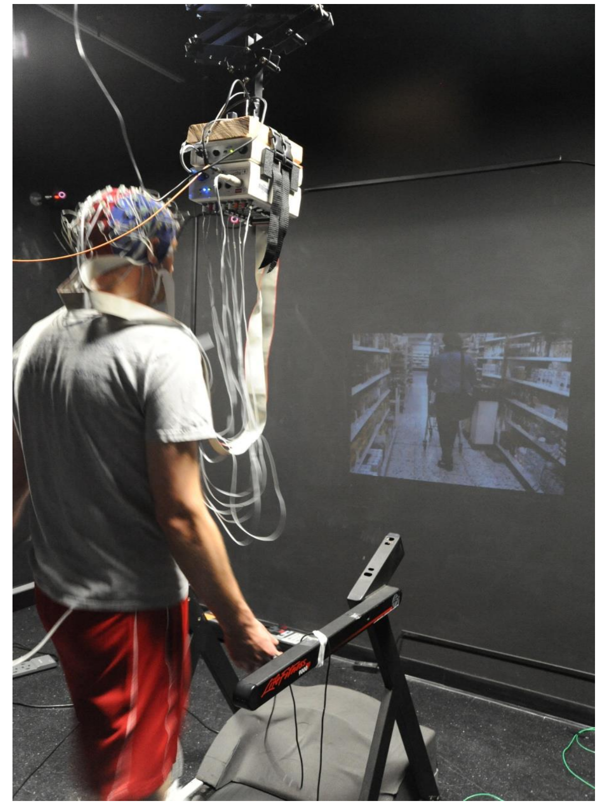
3. **Feasibility of neural recordings while moving**
   1. **Motion Platform**
   2. **Walking**

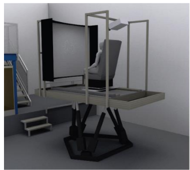
4. Motor preparation in Parkinson's disease

5. Cognitive flexibility of visual load while walking

Virtual reality setups



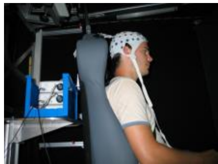




Neuronal Correlates of Self-Motion

- Behavioural tasks
  - Open loop
  - Closed loop

- Imaging techniques
  - fMRI
  - MEG
  - TMS
  - Imaging in non-human primates



Benefits of using EEG

- Systems level snapshot
- Attention deployment
- Temporal resolution
- Light weight
- Real world environment
- Online feedback loop
- …

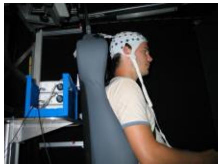
The cusp of a wave

HARDWARE

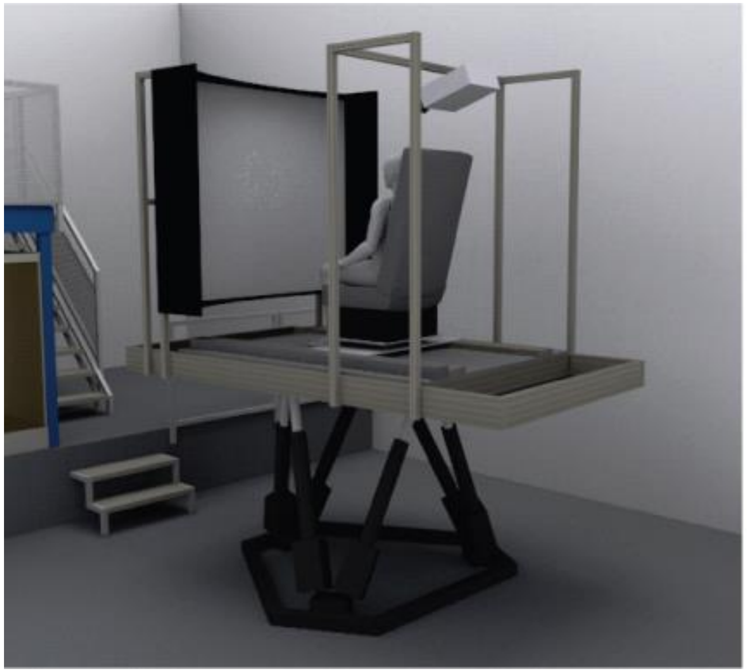
- Advances in motion platform design
- Advances in electrodes design

SOFTWARE

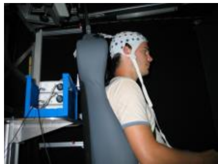
- Advanced analysis techniques
  - Independent Component Analysis
  - Source localisation techniques
  - Mobile Brain Imaging (MoBi – Scott Makeig)
- Individual data analysis
  - Bootstrapped Statistics



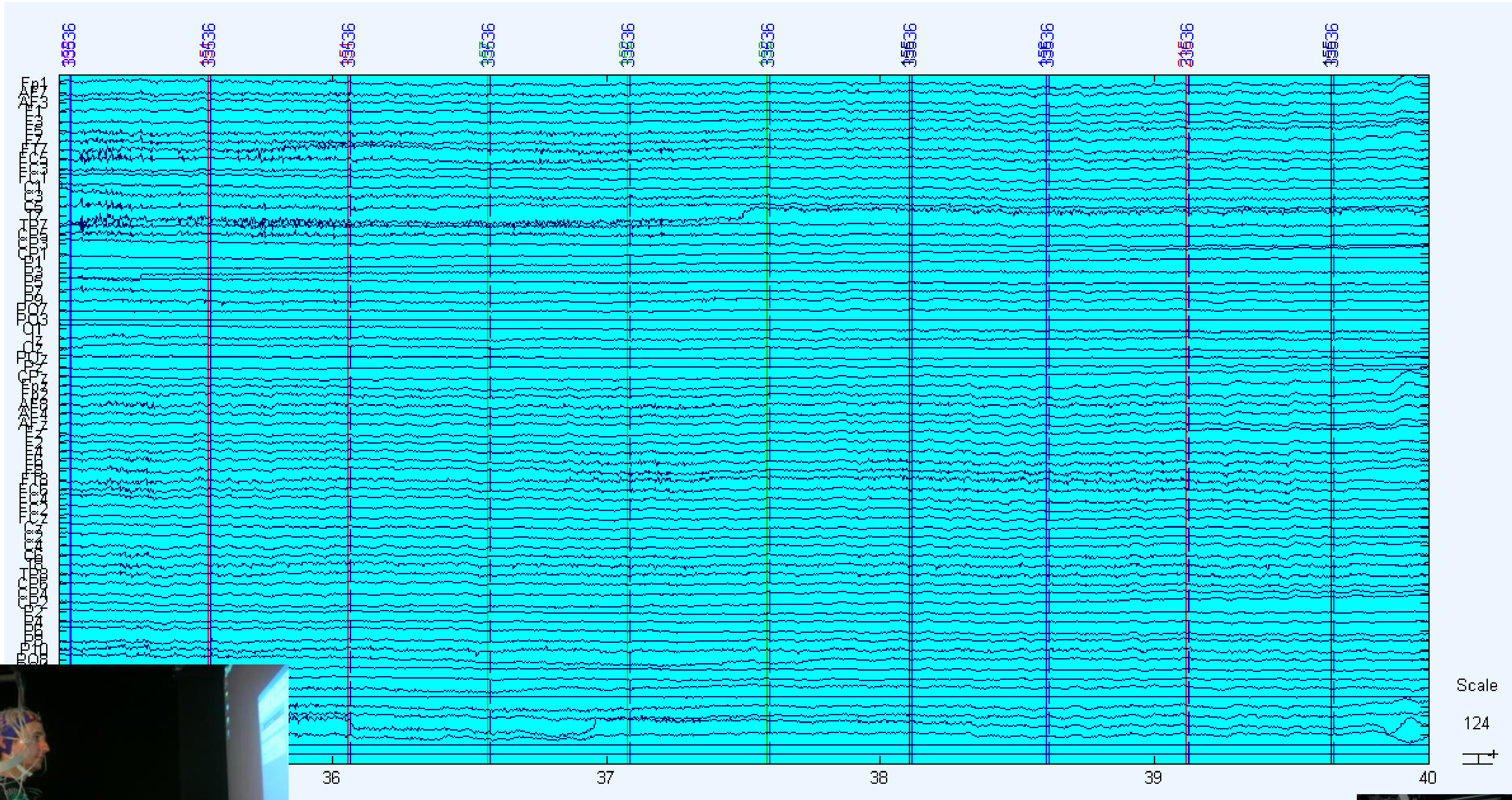
Stewart Platform

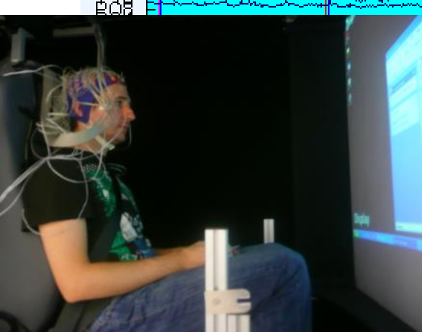


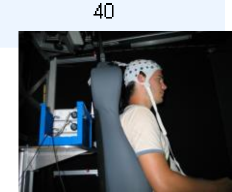
- 6 actuator legs
- 6 degrees of freedom



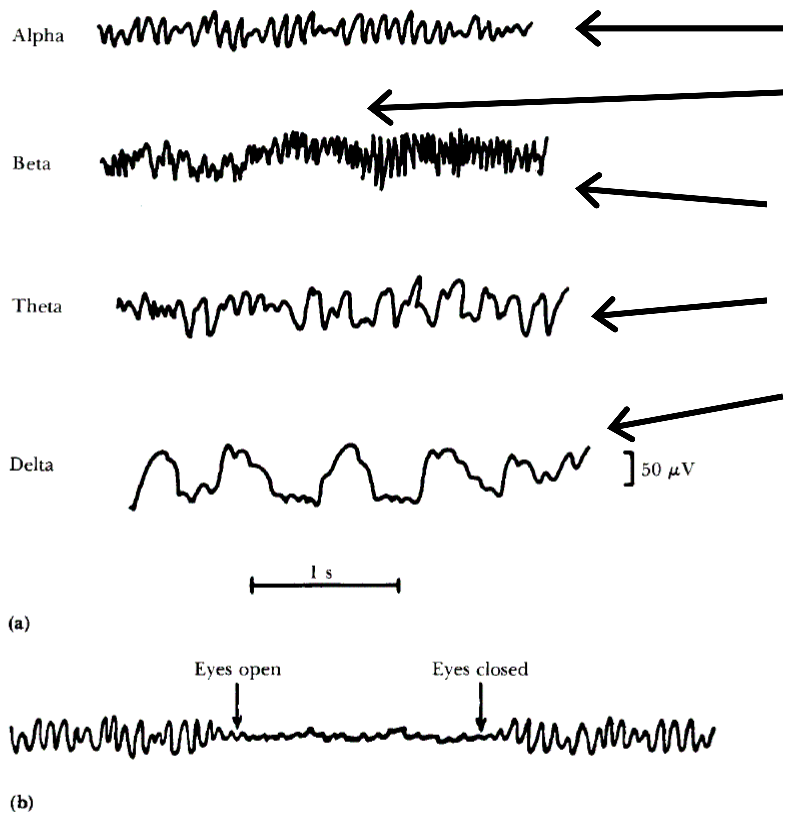
Electroencephalography (EEG)







Frequency decomposition



Alpha 7 - 14 Hz ("~10 Hz")

Beta 14 - 20 Hz

Gamma > 20 Hz ("~40 Hz")

Theta 3 - 7 Hz

Delta 0.5 – 3 Hz

Hans Berger:

First Human EEG recording in 1929

- Alpha waves discovered

Feasibility of EEG on a Stewart platform

PARTICIPANT ARTIFACTS

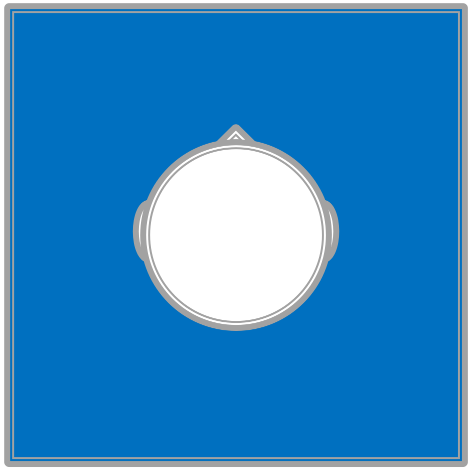
- Eye movements
- Laughing
- Blinking
- Neck movement
- …

EXTERNAL ARTIFACTS

- Phones
- Screens
- Headphones
- Plugs
- …

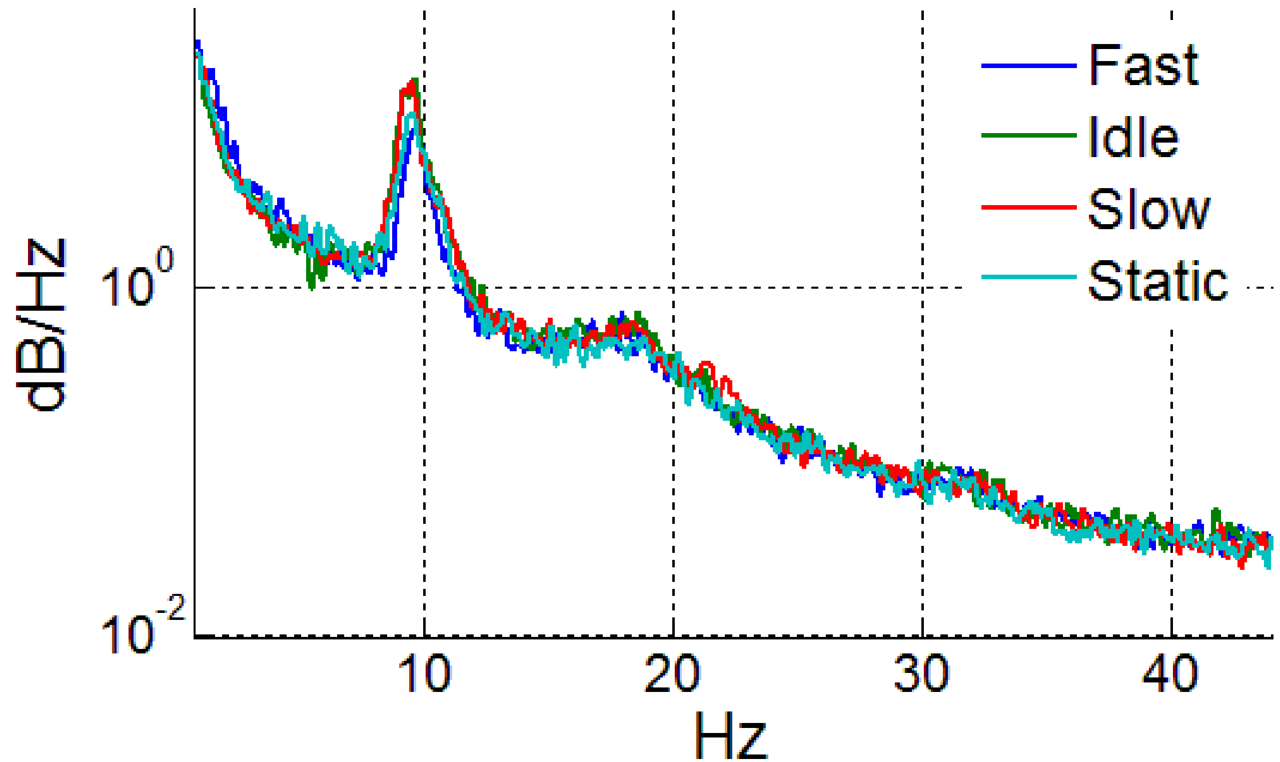
The Movement Paradigm

- Four levels of motion
  - Stationary
  - Idle
  - Slow 0.5 hrtz at 0.25mG
  - Fast 0.5 hrtz at 0.75mG



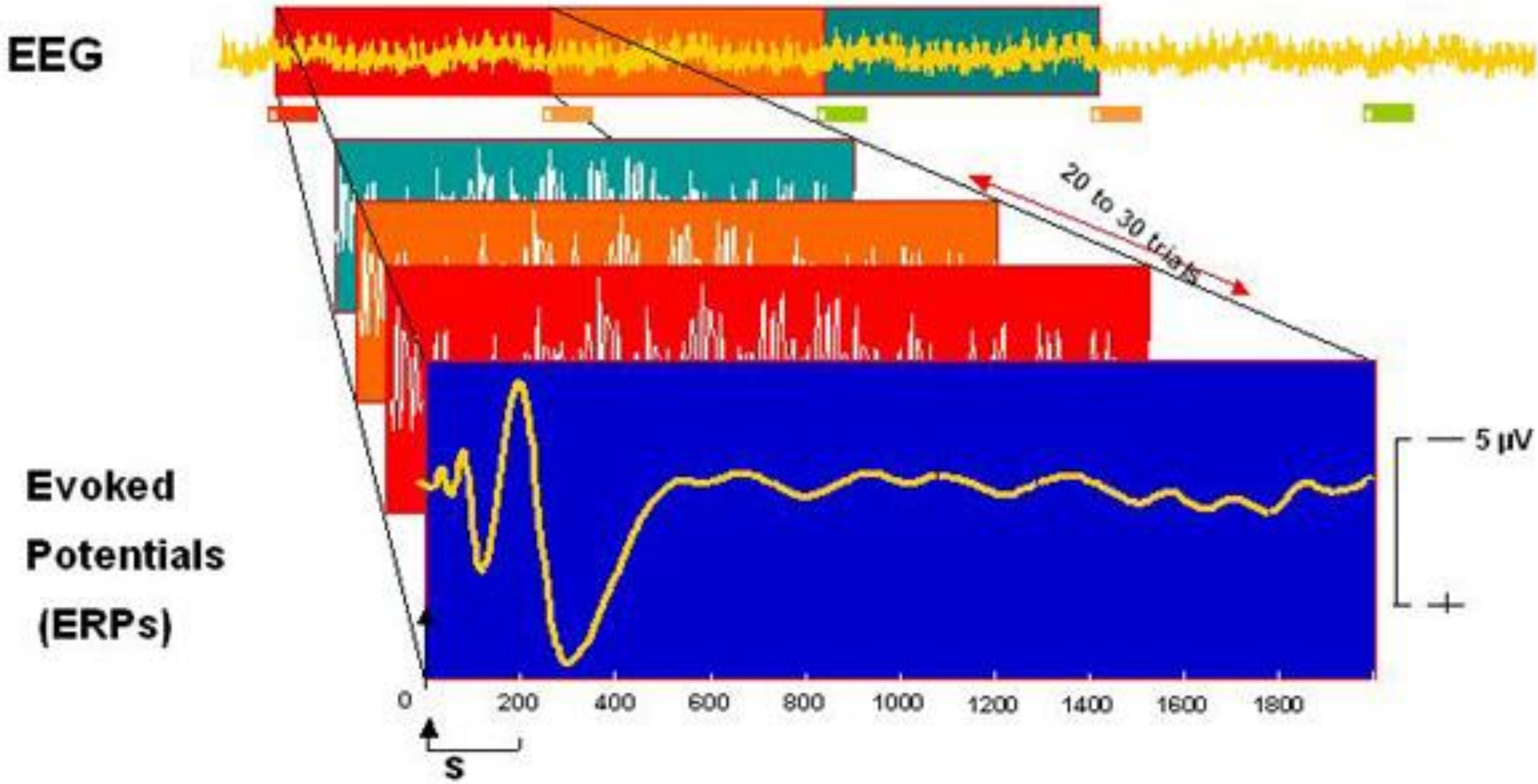
Results - Control Experiment

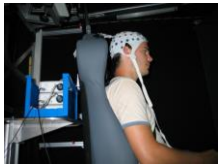
EEG can be conducted on a moving motion platform



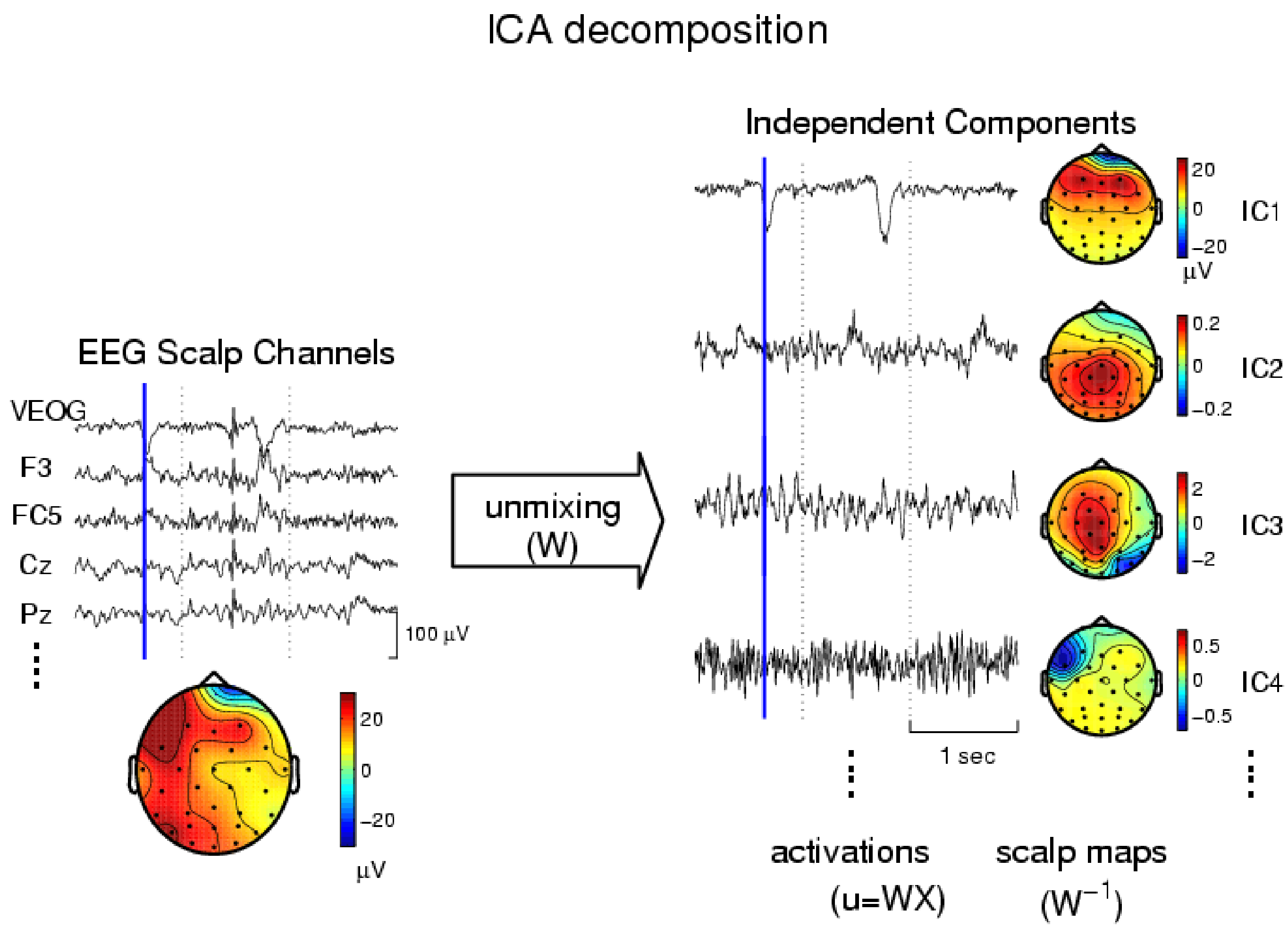
Nolan, Whelan, Foxe, Bulthoff, Reilly, Butler (2009)

Event-Related Potential (ERPs)



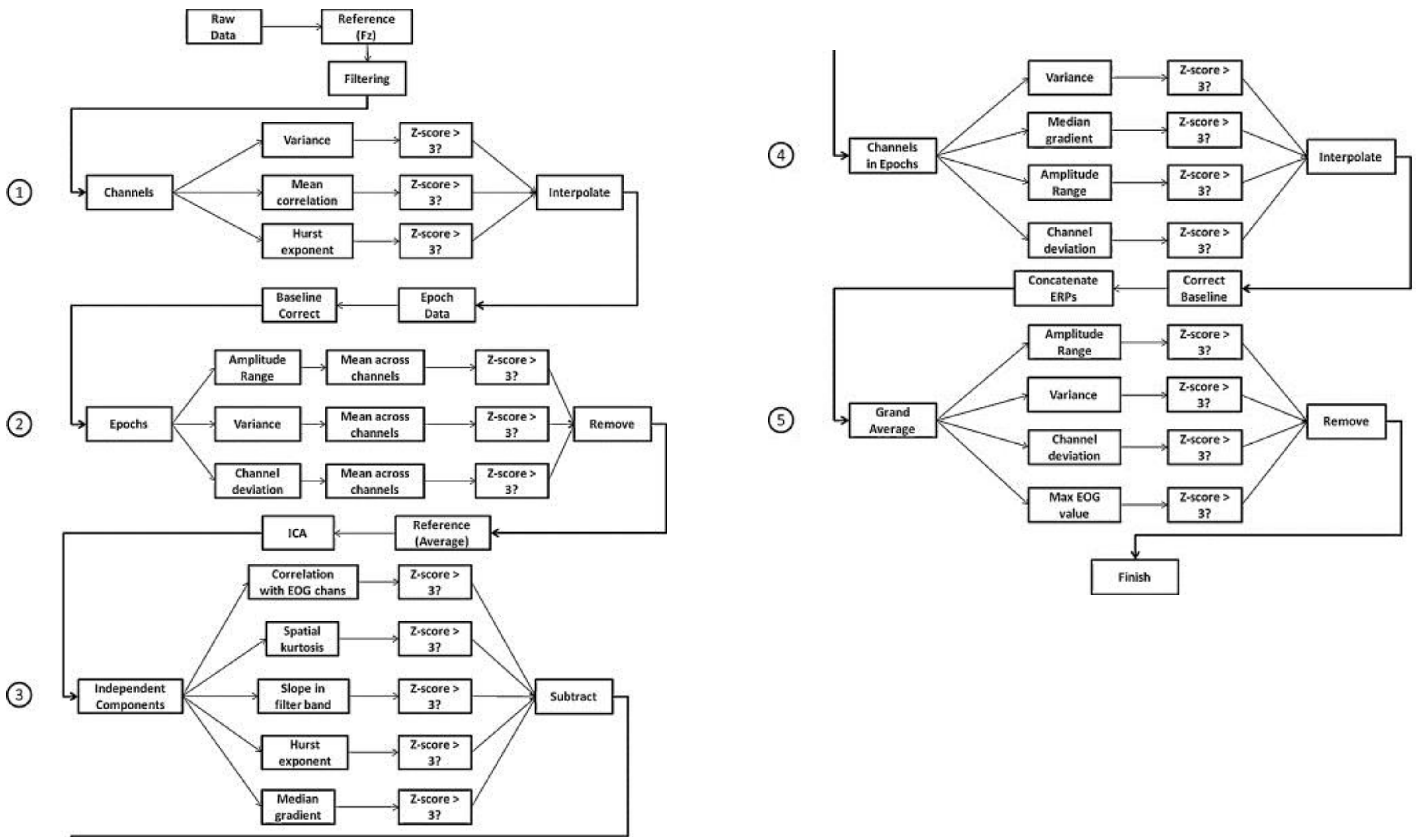


Independent Component Analysis

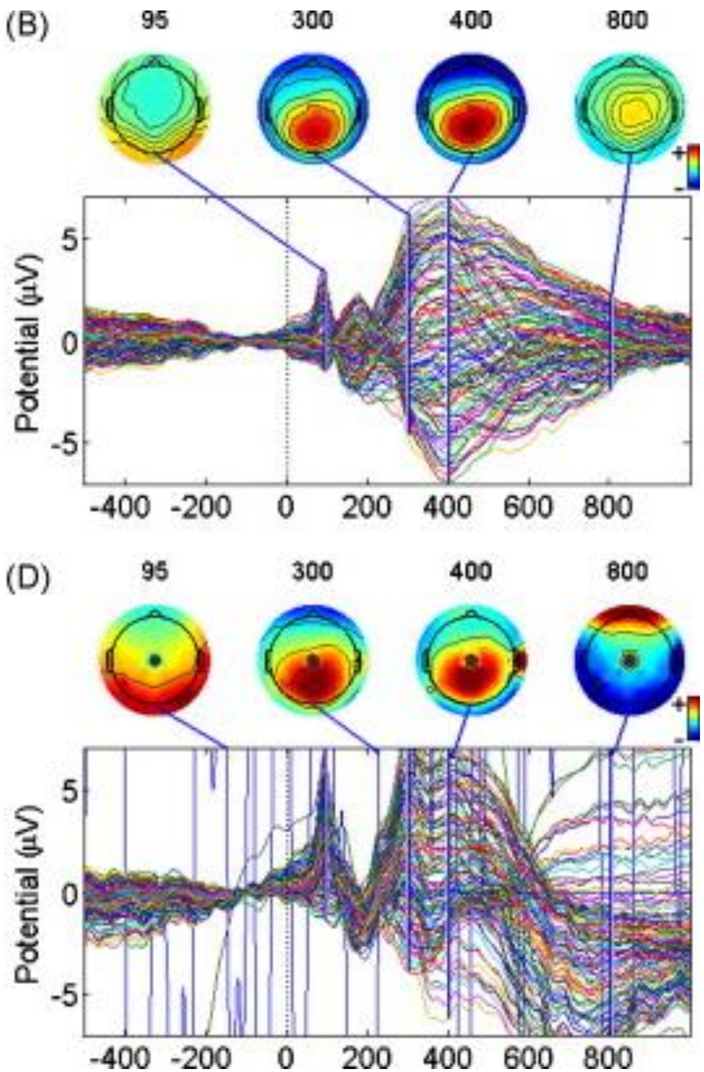


Jung T-P, Makeig S, Humphries C , Lee TW, McKeown MJ, Iragui V, and Sejnowski TJ (2000)

Fully Automated Statistical Thresholding for EEG artefact Rejection



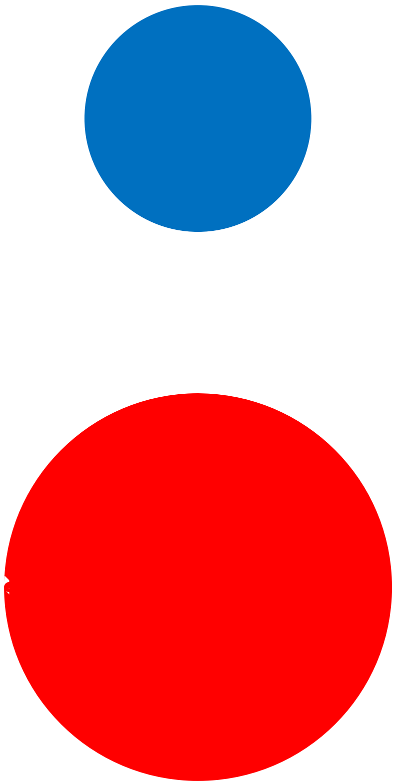
Fully Automated Statistical Thresholding for EEG artefact Rejection



Nolan, Whelan, Reilly (2010)

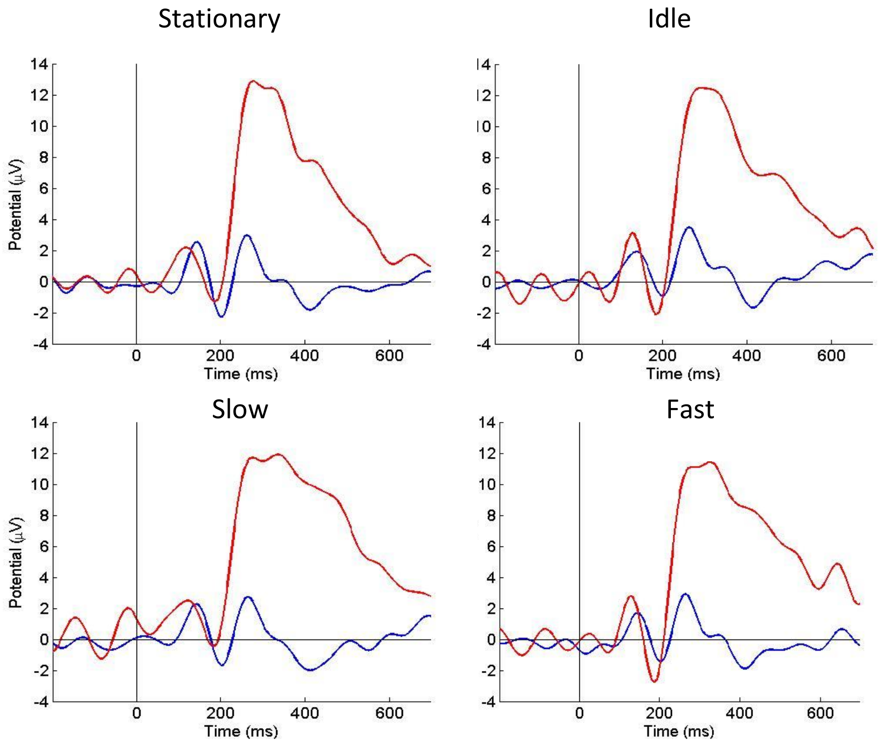
The Oddball Paradigm

- Can we get an EEG signal while moving people?
- Visual P3 paradigm
  - 80% Standard
  - 20% Target
- Four levels of motion
  - Stationary
  - Idle
  - Slow 0.5 hrtz at 0.25mG
  - Fast 0.5 hrtz at 0.75mG



SSSTSSSSTSSSTSST

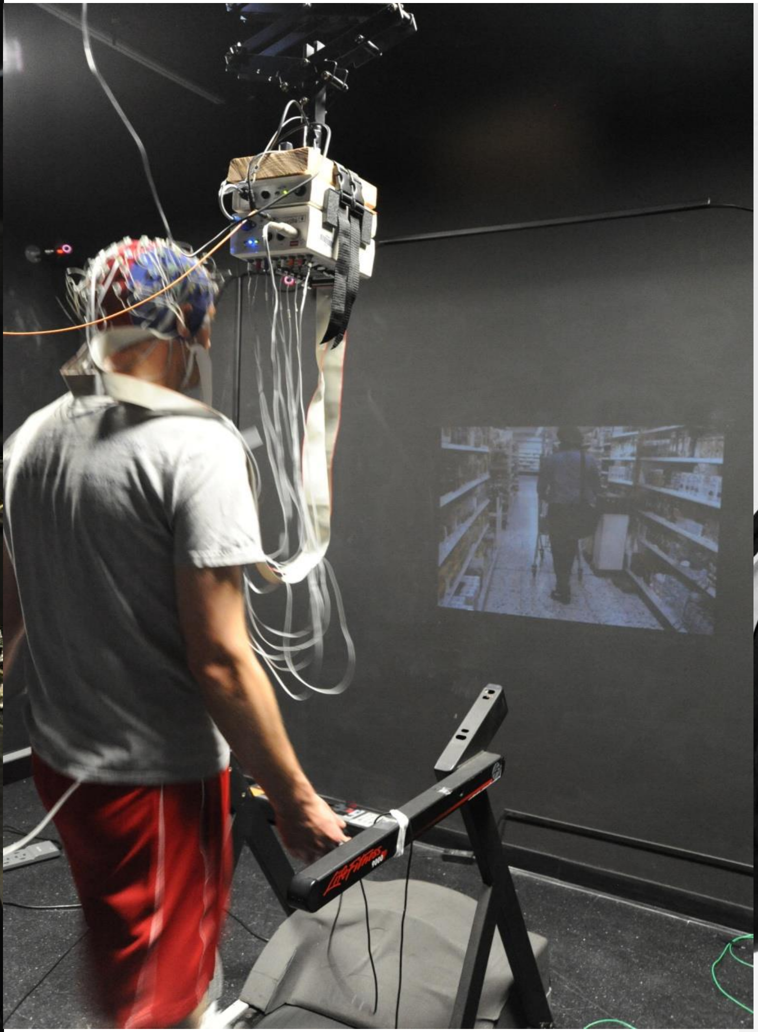
Results - Control Experiment



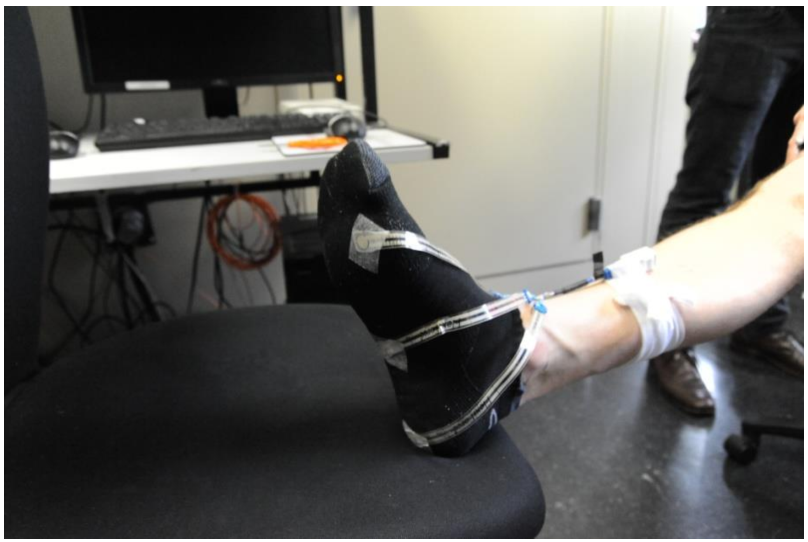
A difference was shown between the standard and target.

Nolan, Whelan, Foxe, Bulthoff, Reilly, Butler (2009)

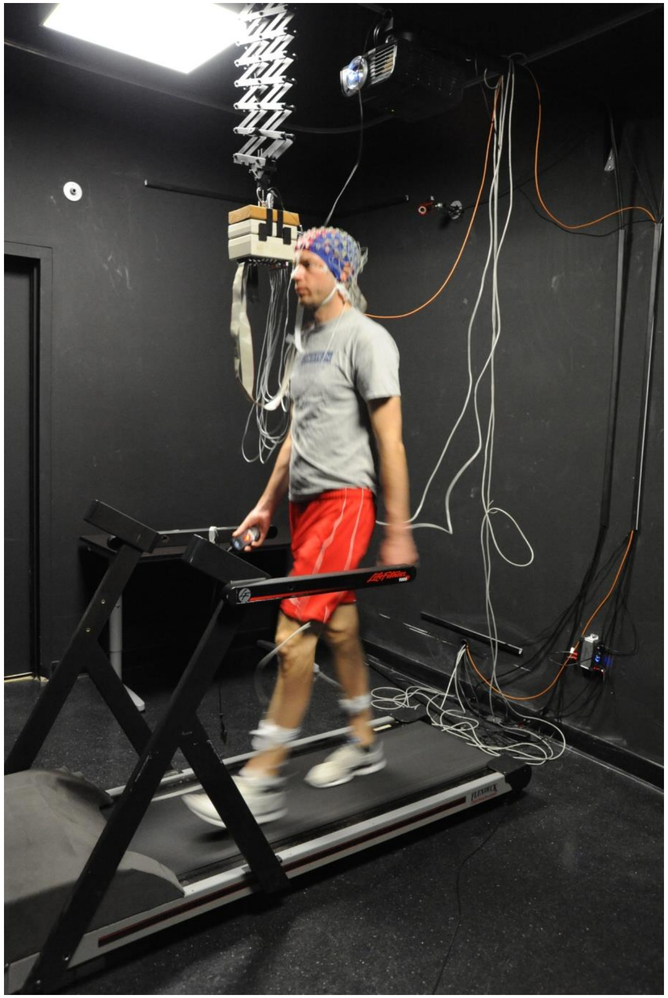
EEG while Walking



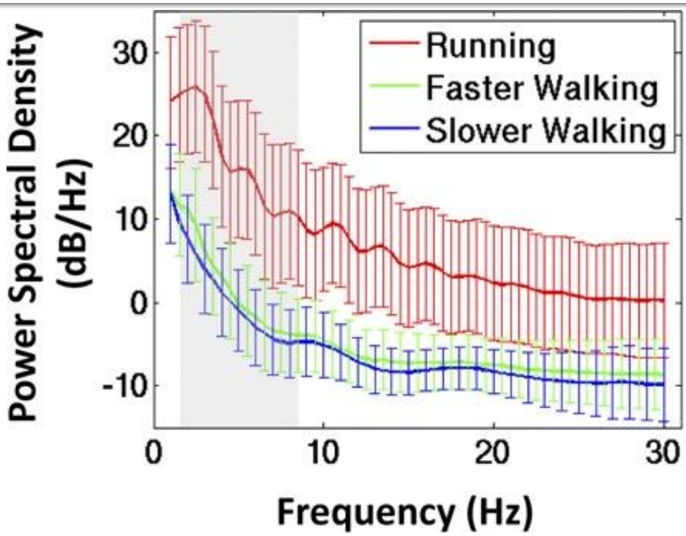
EEG while Walking

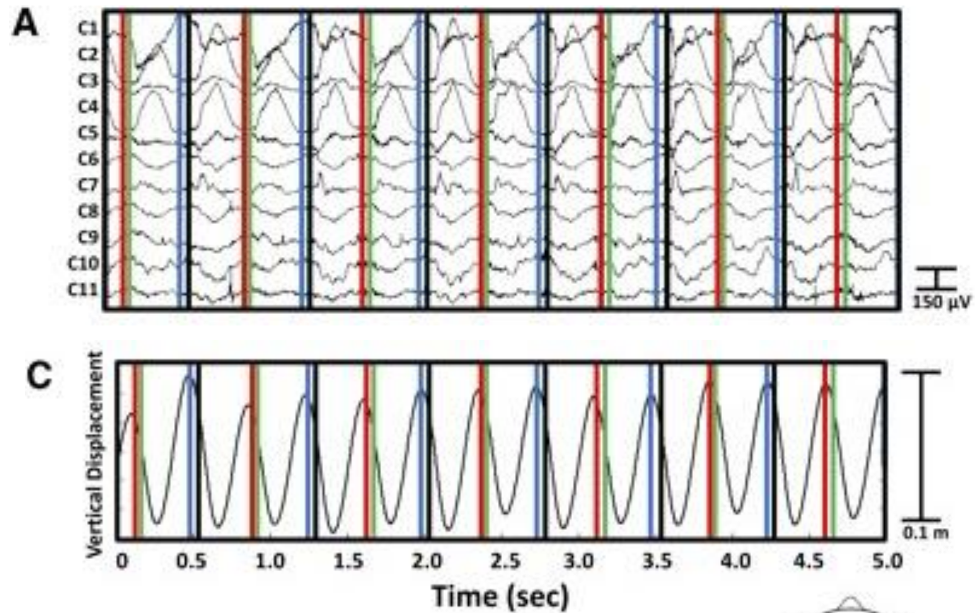


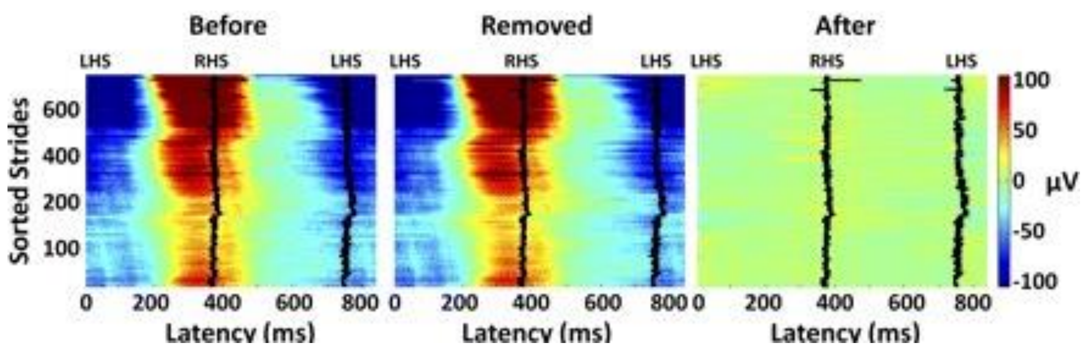
EEG while Walking



Signal Issues with Walking



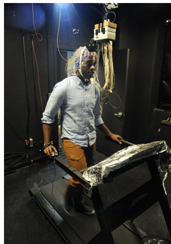




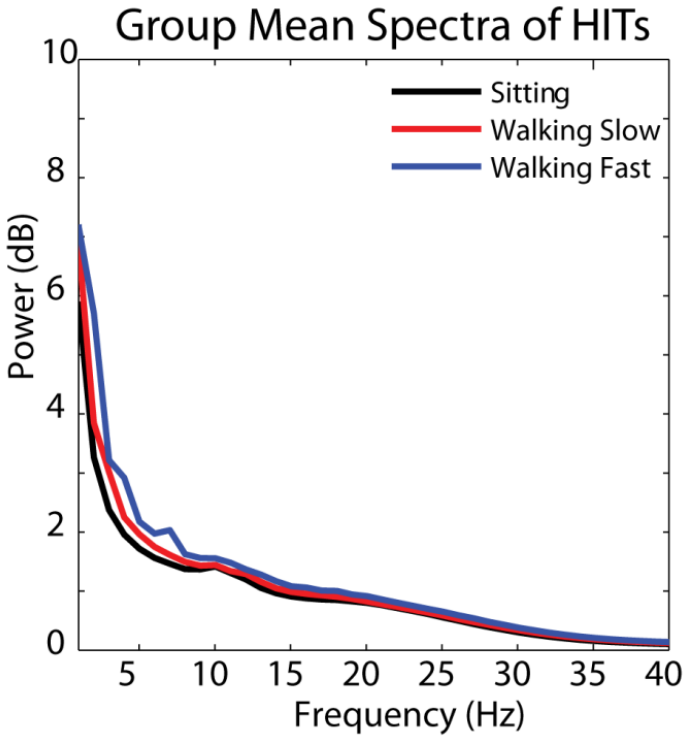
Adapted from Wagner et al. 2016, *J. Neuro*

Response Inhibition Task

- Hit:
  - correct response in a *go* trial
- Correct Rejection:
  - successful withholding of a response in a *nogo* trial
- False Alarm:
  - Executing a response in a *nogo* trial

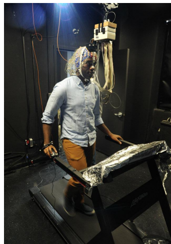


Feasible to acquire usable EEG data



	Sitting	Walking Slow	Walking Fast
SNR Hit (dB)	54.8±2	53.6±1.6	49.9±2.2
SNR CR (dB)	35.3±2	34.0±2.5	32.6±2.2

Highly similar early evoked response and power spectrum point to the feasibility of acquiring EEG while walking



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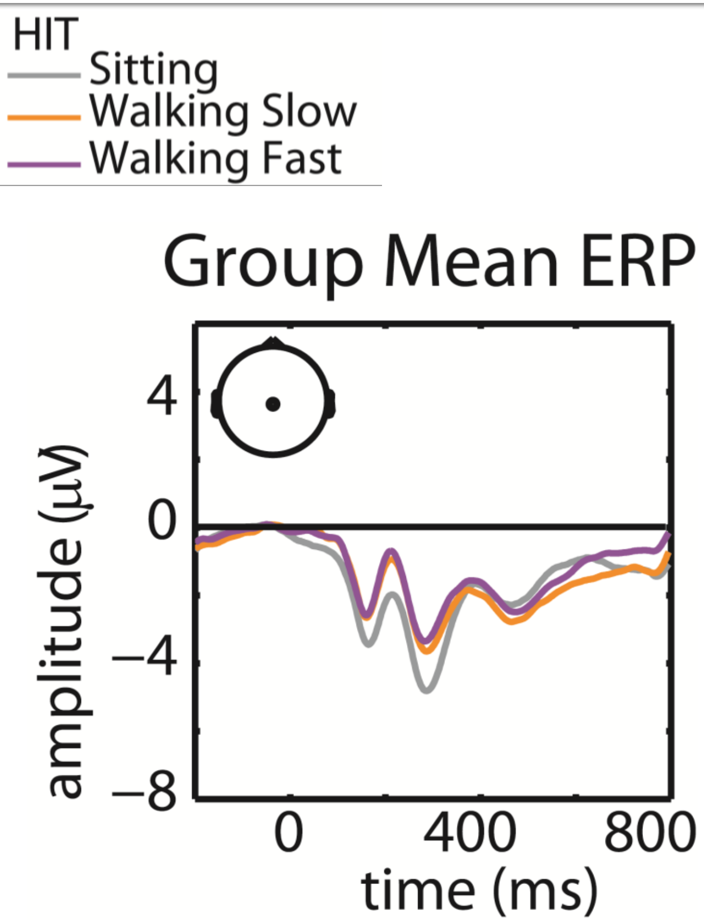
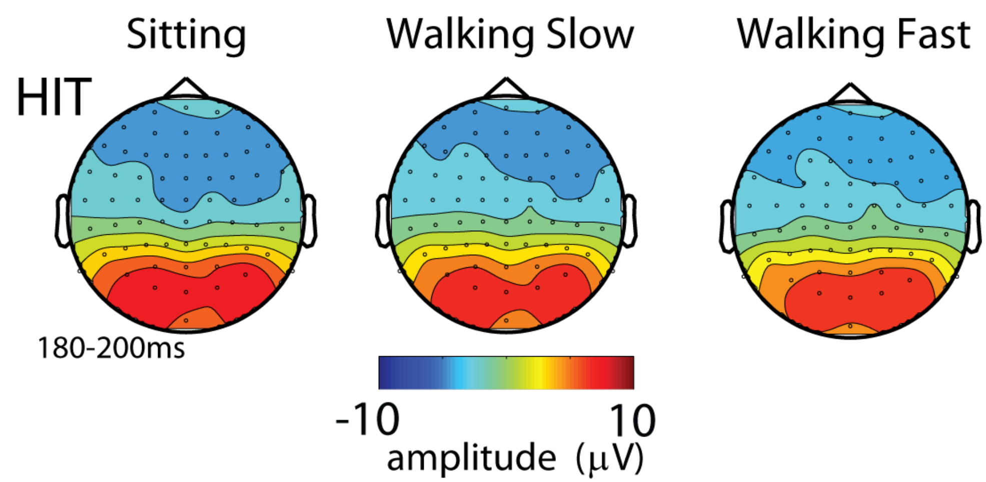
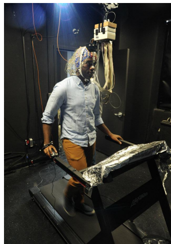




34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

De Sanctis, Butler*, Green , Snyder, Foxe (2012)



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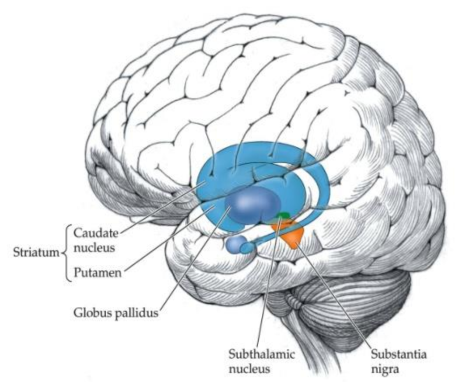
1. Introduction
2. Distance Perception
3. Feasibility of neural recordings while moving
4. **Motor preparation in Parkinson's disease**
5. Cognitive flexibility of visual load while walking

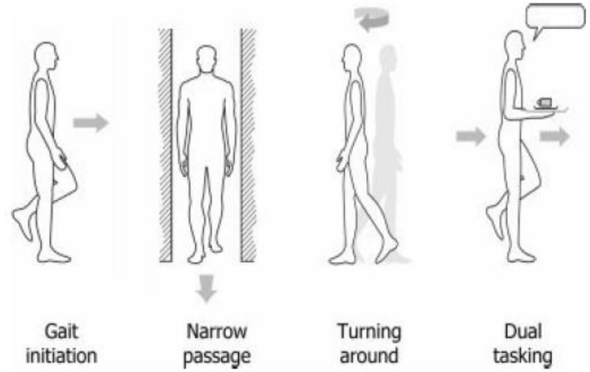
Parkinson’s Disease

- Parkinson’s disease (PD): neurodegenerative disorder characterised by loss of dopaminergic signalling in the basal ganglia
- Motor symptoms
  - Tremor
  - Bradykinesia
  - Rigidity
  - Postural disturbance
  - <u>Freezing of gait</u>
- Non-motor features: constipation, depression, anxiety, cognitive impairment, autonomic instability, hallucinations and impulse control disorders.
- Treatment: dopamine replacement or deep brain stimulation

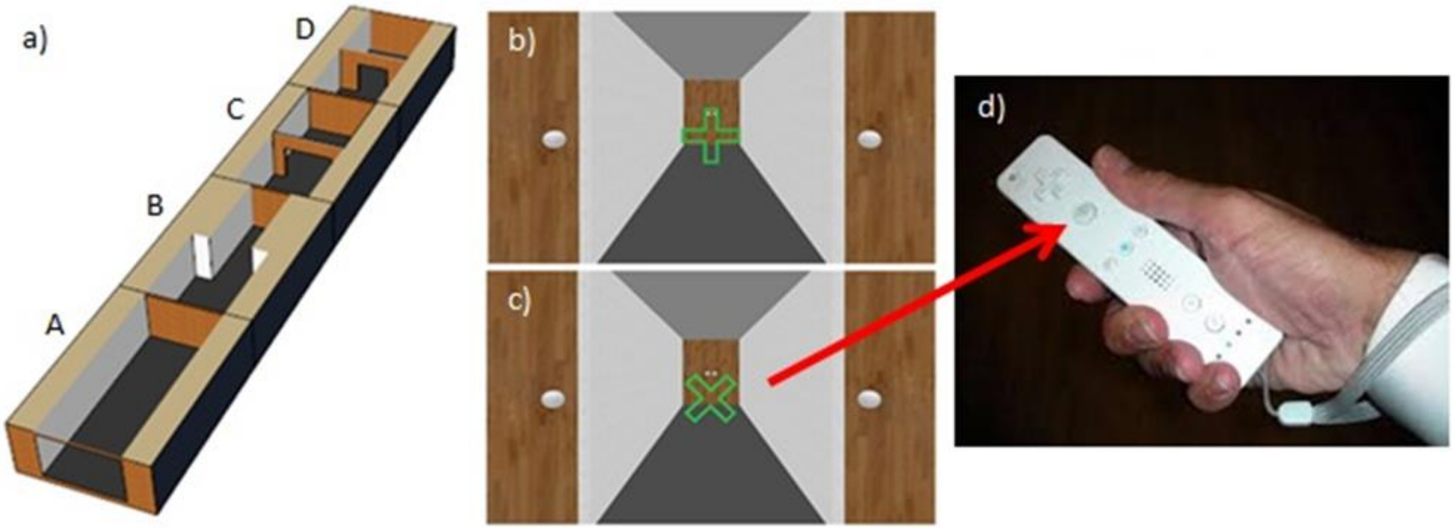


Freezing of Gait

- Intermittent gait disturbance - feet glued to floor
  - Most apparent in late-stage Parkinson's disease
- Affects up to 60% patients with Parkinson's disease
- Causes falls
- Poorly understood
  - No effective treatments
  - Difficult to study
  - Heterogeneous



Dual Task

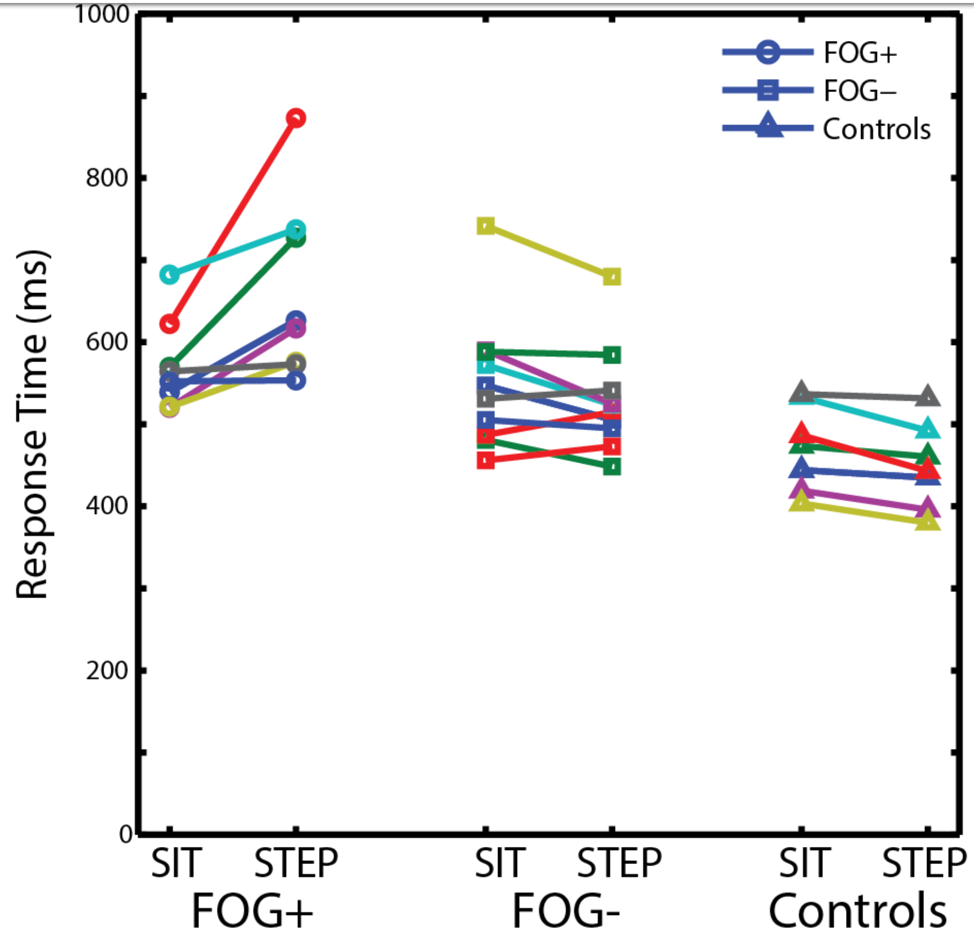


Oddball task while Stepping in Place

	FOG+	FOG-	Controls
N	8	10	7
Age (years)	65.7	62.5	25
Gender (M:F)*	7:1	4:6	3:4
H&Y stage	2.6	2.3	
Disease Duration (years)*	12.3 (8.36)	7.0 (3.6)	
UPDRS III	28.6	29.1	
MOCA	24.0	26.1	
FAB*	14.9	17.3	

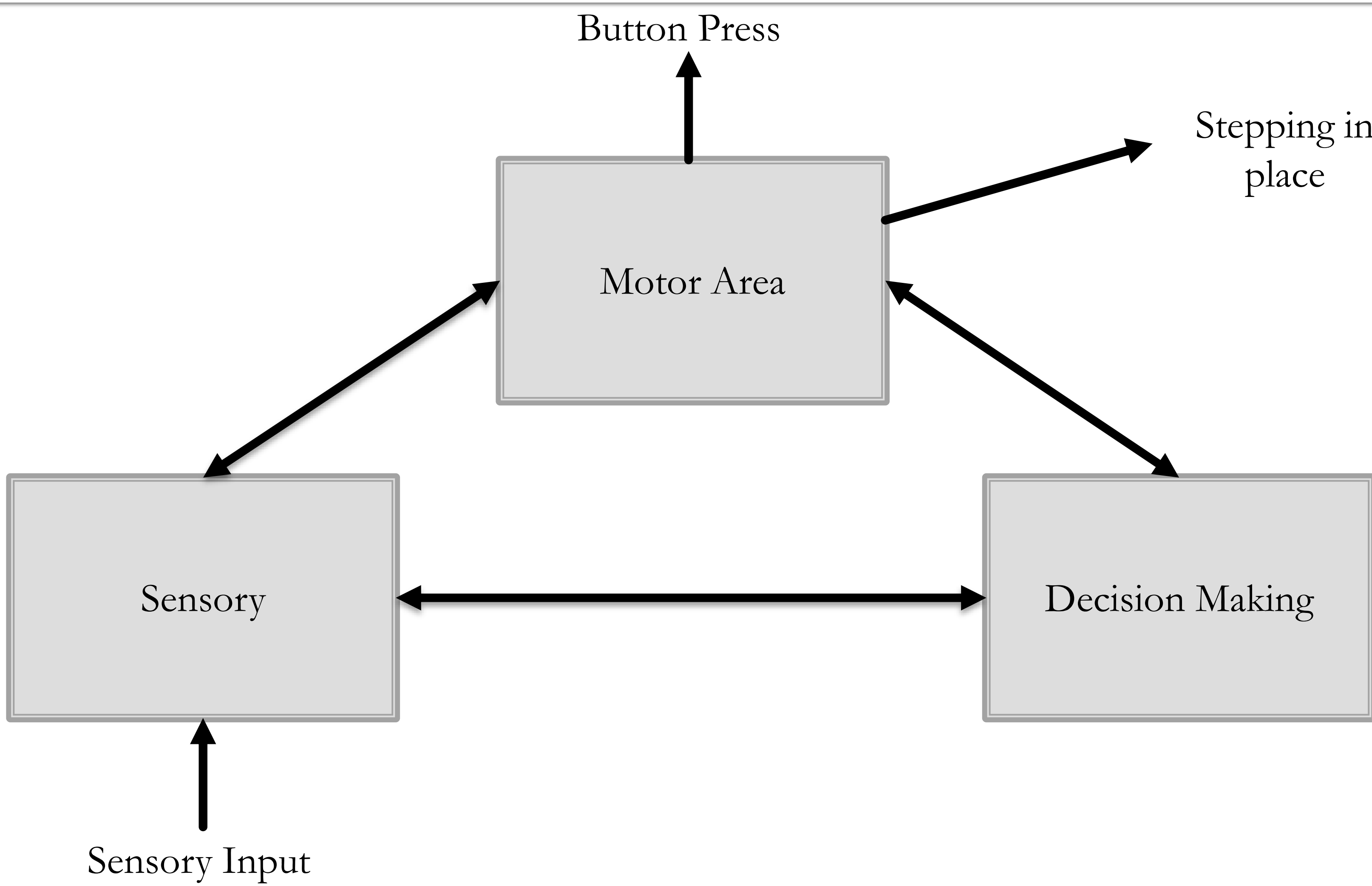
- Standard (80%)
- Target (20%)
- Button Response
- 1000ms epochs
- 128 channels

Behavioural

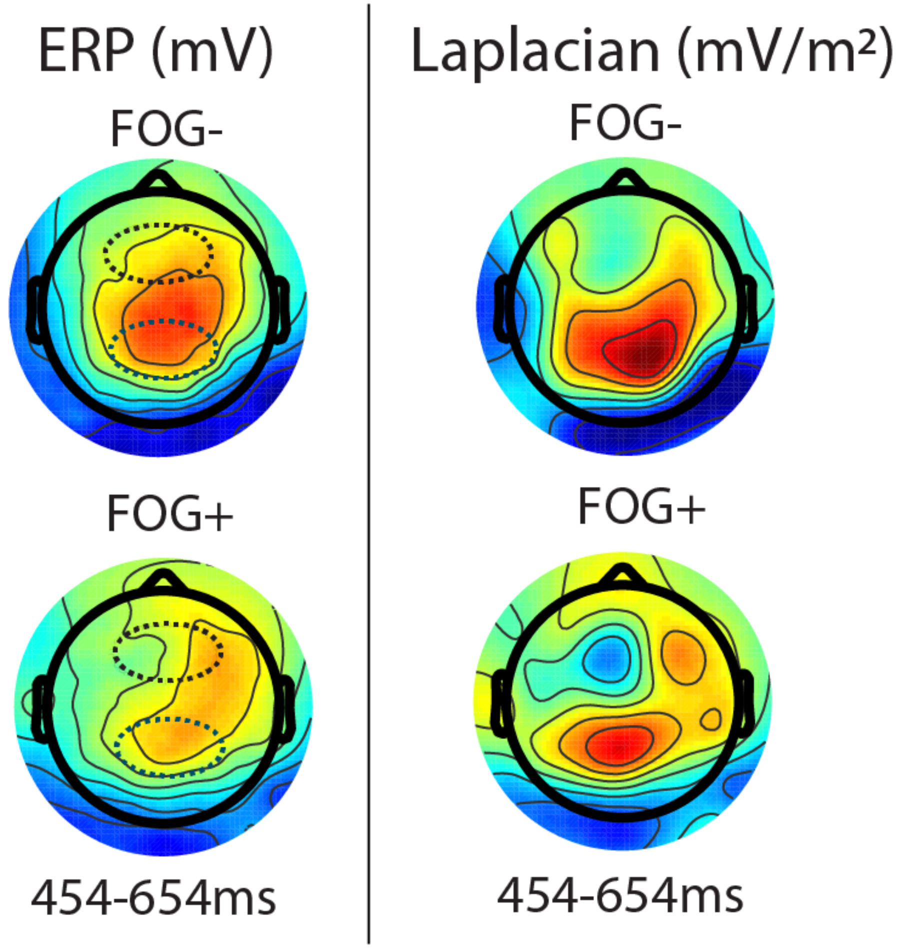


Significant interaction of Response Times for group (FOG+, FOG-, Controls) and condition (SIT, STEP)

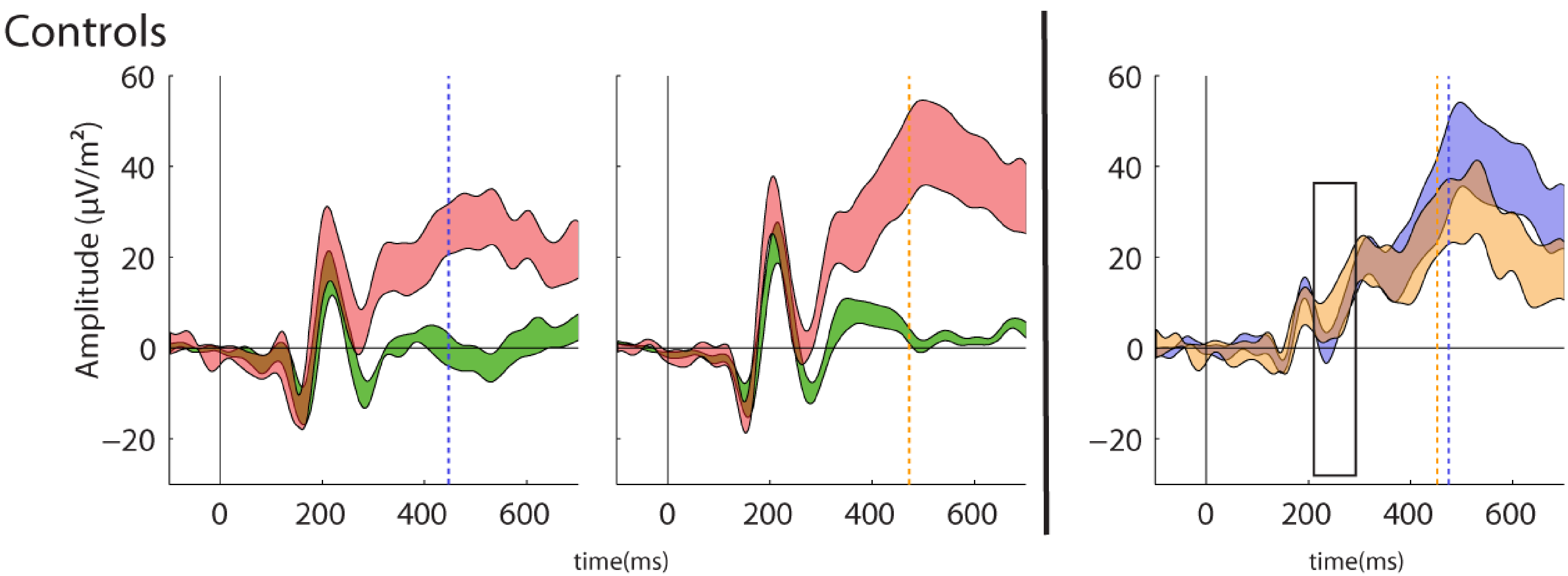
Sensory Motor Decision Making



Laplacian (Second Order Spatial Derivative)

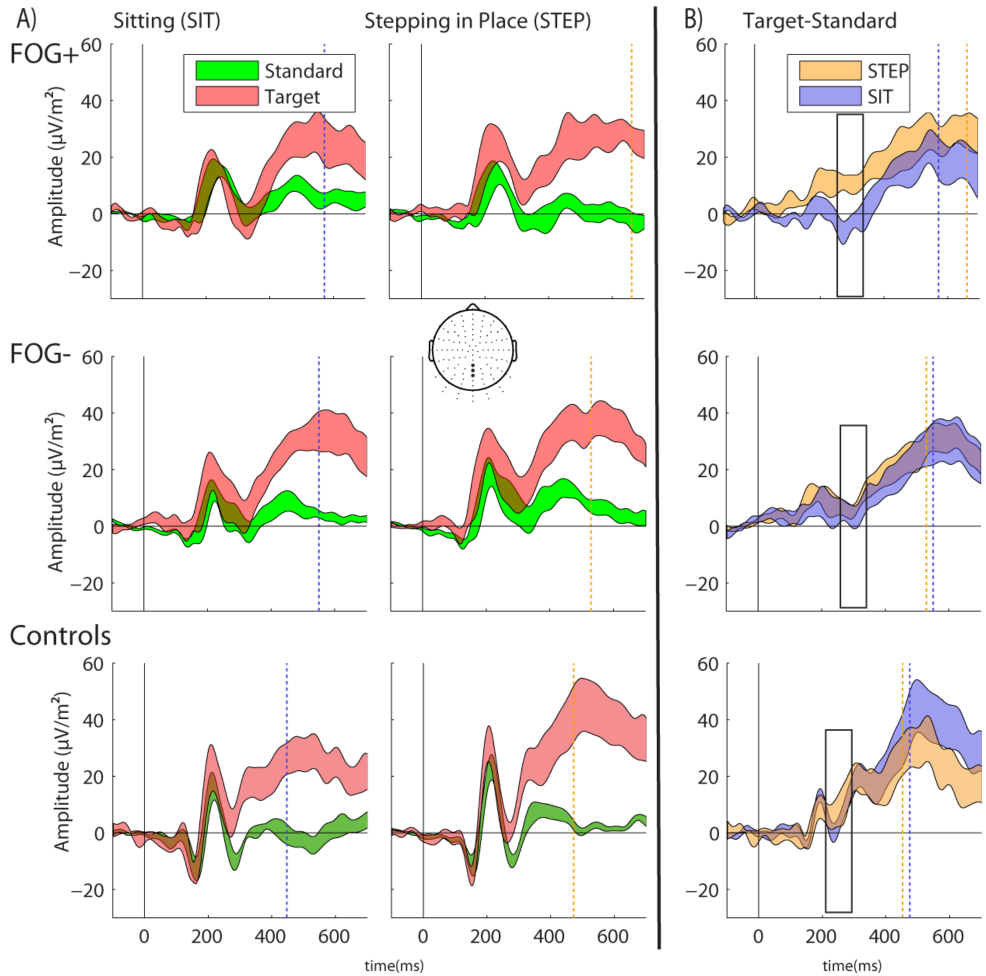


Standard vs Target



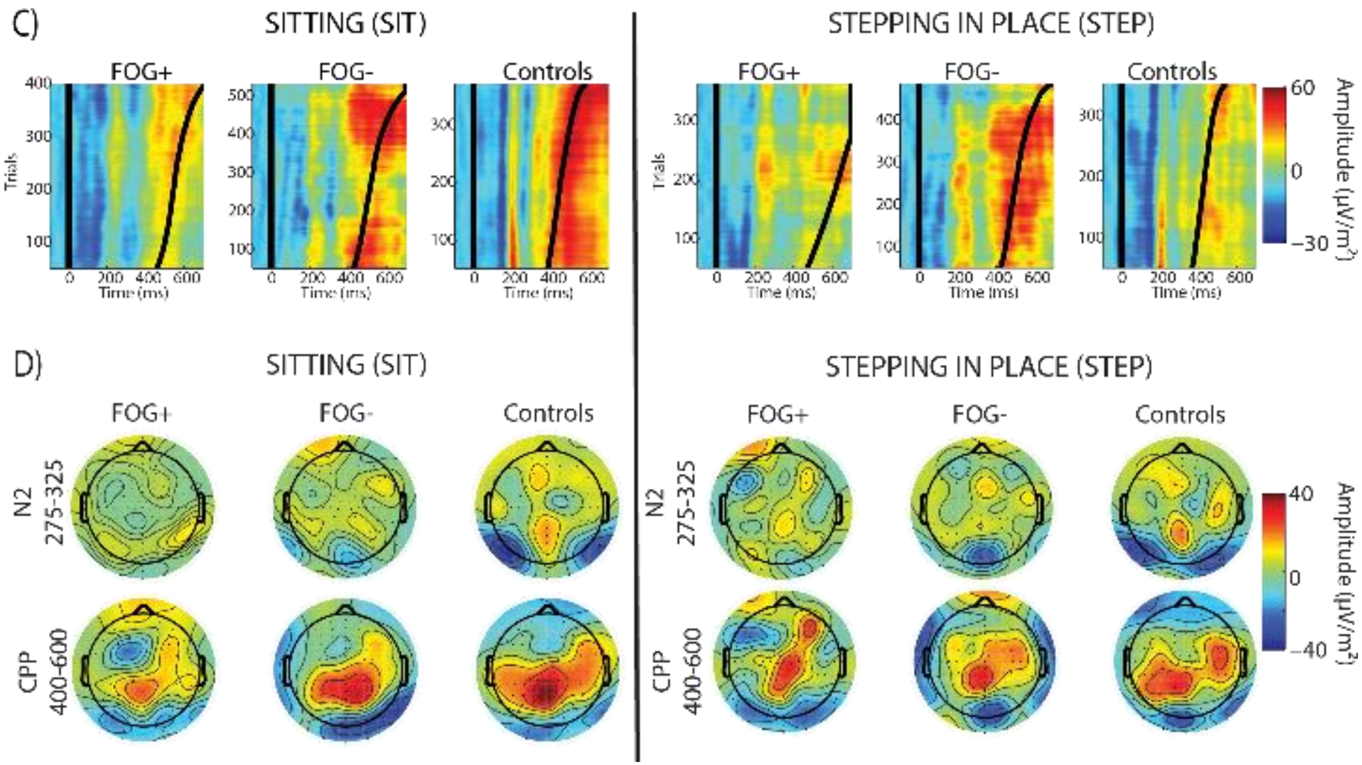
Relatively clean data for both sitting and stepping in place

Standard vs Target



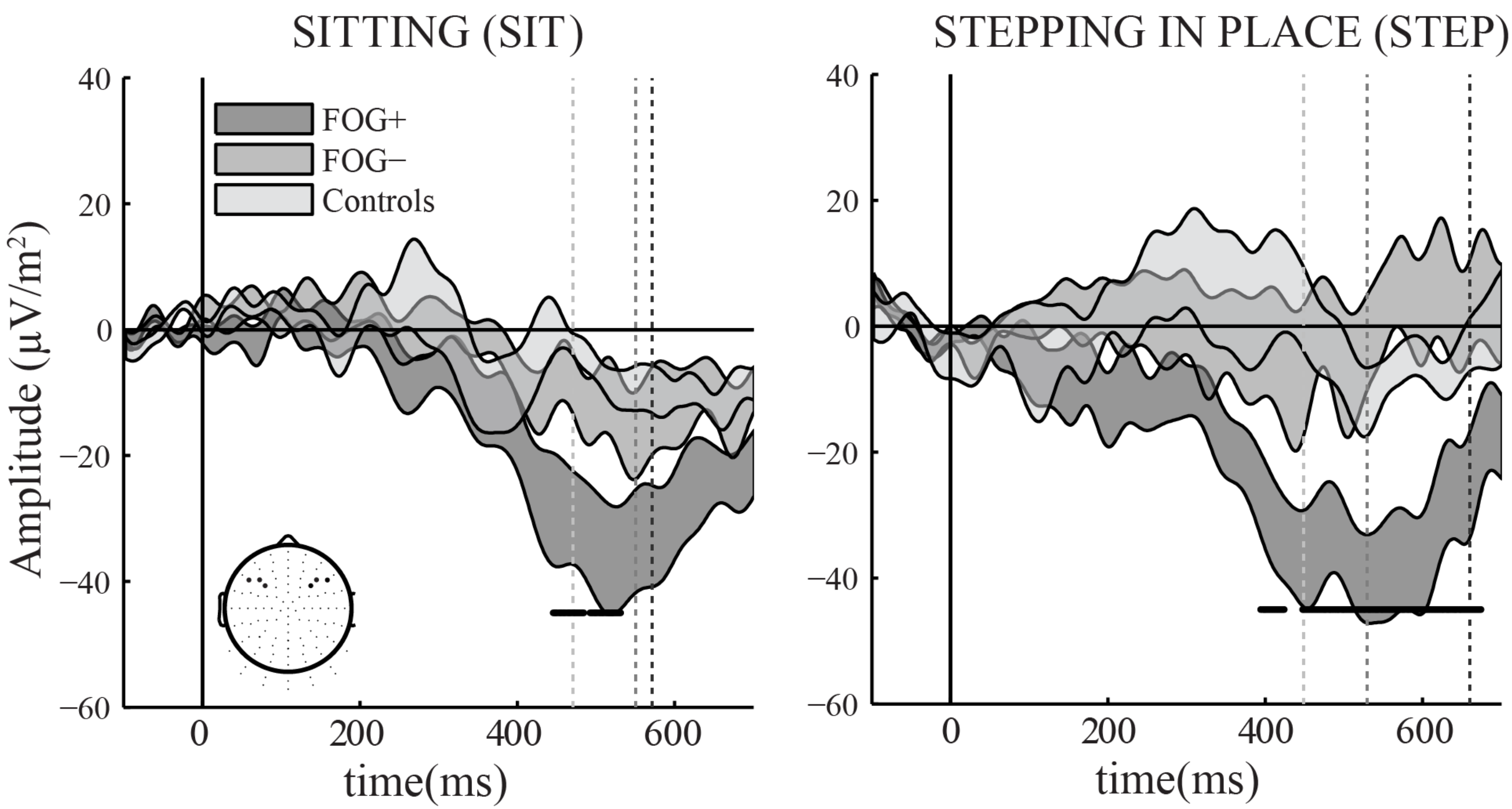
Relatively clean data for both sitting and stepping in place

Automatic (N2) and decision (CPP) response



Automatic response (N2) is absent in FOG+ while stepping in place

Readiness Potential



Earlier onset and larger motor response for the FOG+ group

Summary III

- With the added load of stepping in place FOG+ response times were slowed
- Absence of N2 suggests that early "automatic" resources are being re-allocated
- The larger and earlier onset of the LRP while walking illustrates the recruitment of resources to perform the task

Butler*, Fearon, Kilane, Waechter, Reilly, Lynch (2017)

Talk Overview

1. Introduction
2. Distance Perception
3. Feasibility of neural recordings while moving
4. Motor preparation in Parkinson's disease
5. **Cognitive flexibility of visual load while walking**

Visual Load

- Participants: 16 young adults (mean age = 26 years)
- Self-selected treadmill walking speed (average = 3.9 km/h)
- Experimental conditions
  - **Cognitive Load:**
    - Engage in task
    - Walking only (do not engage in task)
  - **Visual Load:**
    - Static star field
    - Optic flow no perturbations (NOP)
    - Optic flow mediolateral perturbations (MLP)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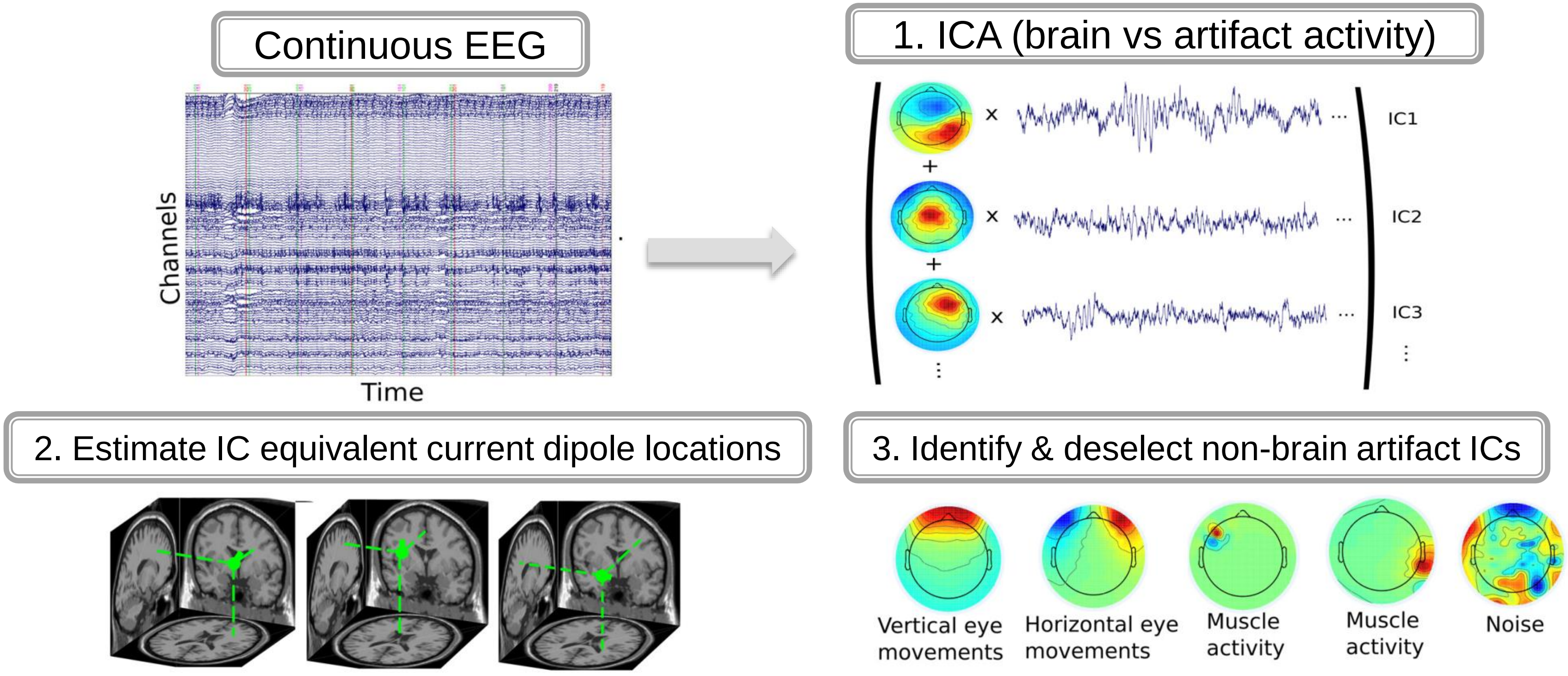
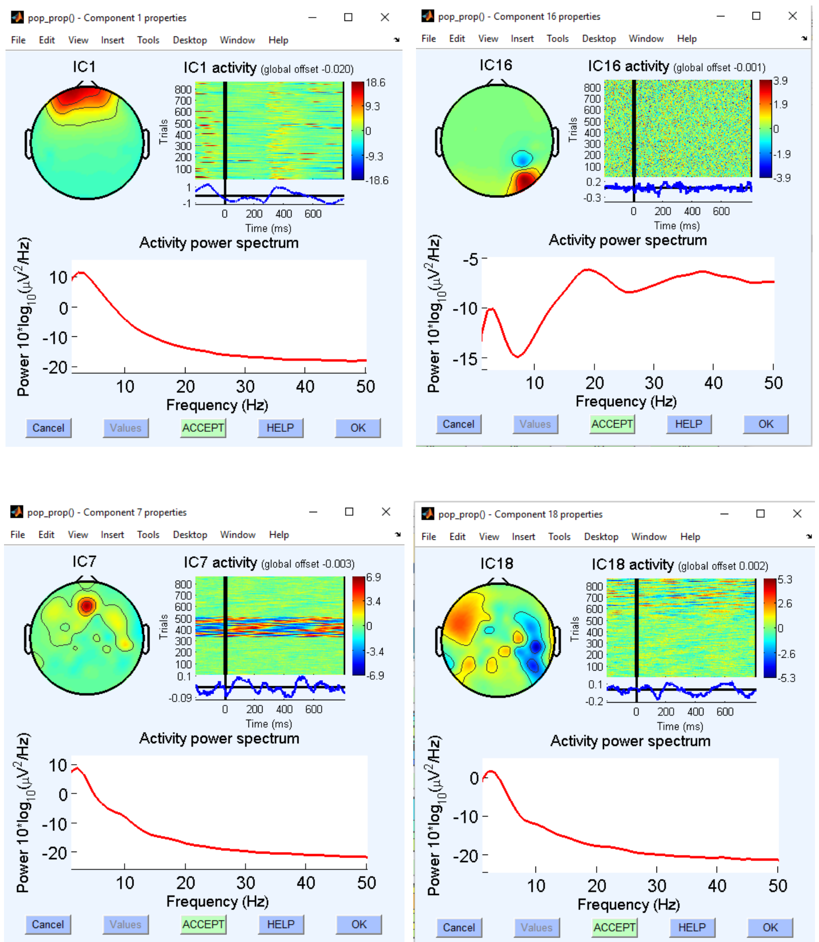
Methods: ICA and clustering analysis



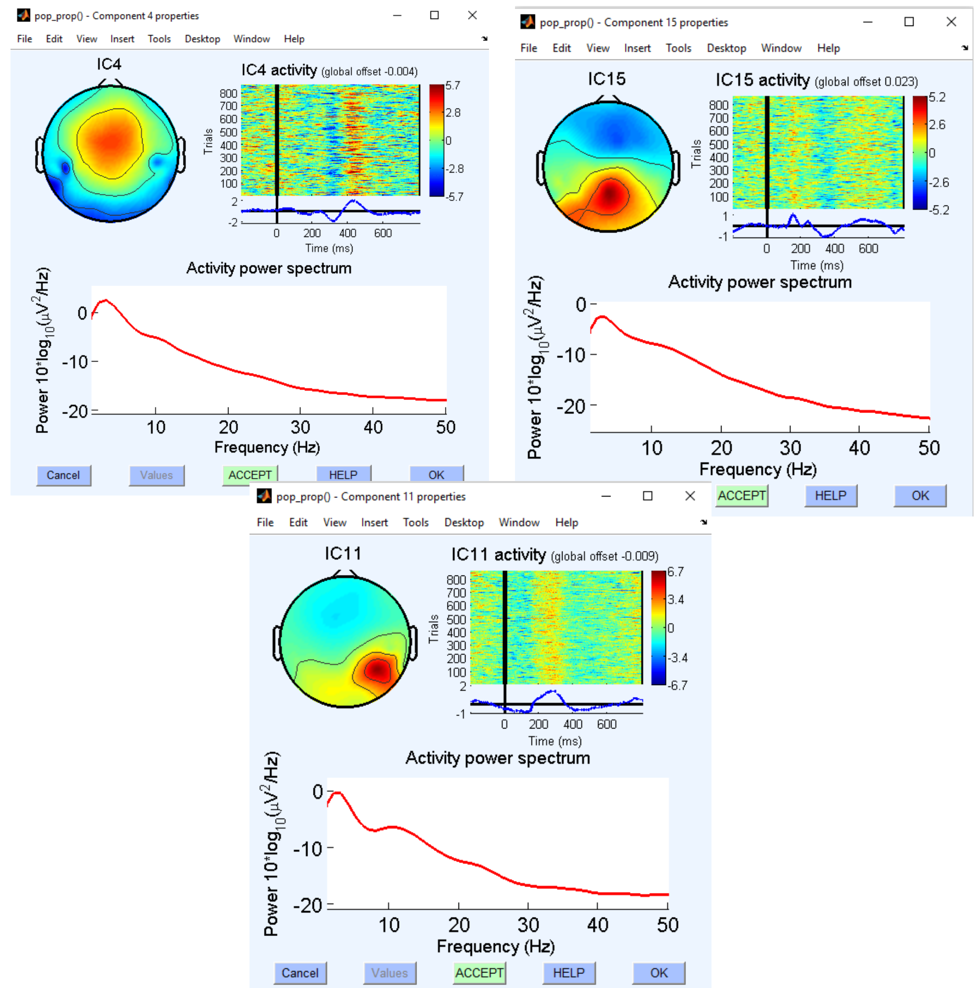
Adapted from Wagner et al. 2016, *J. Neuro*

ICA artifact rejection

Artifactual Components

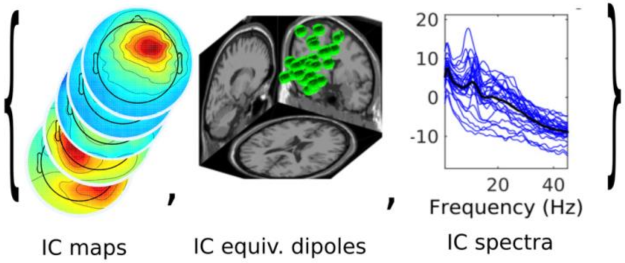


Brain Components

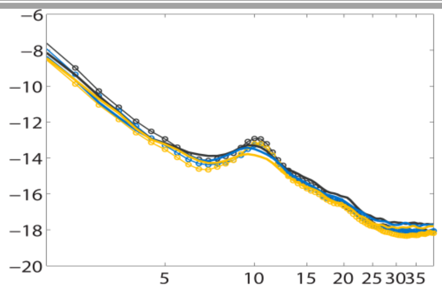


Methods: ICA and clustering analysis

4. Cluster remaining brain ICs across subjects, based on:

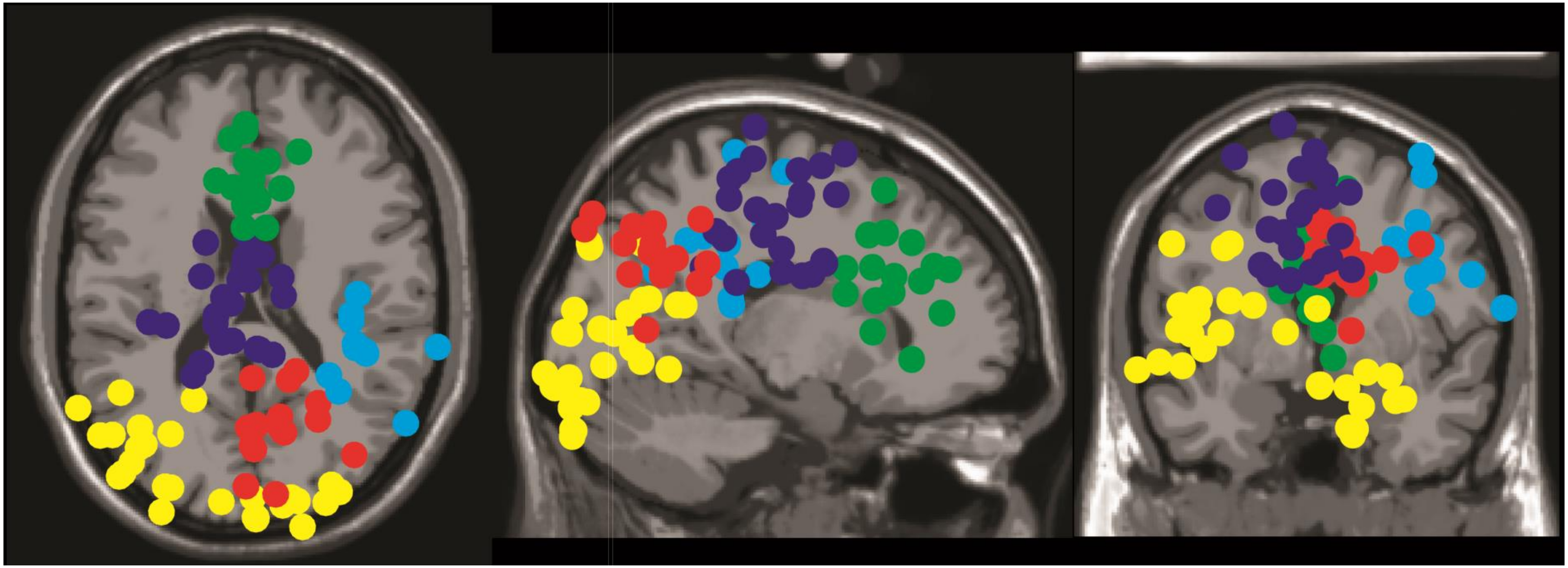


5. Average IC periodograms across each cluster, for each condition



Adapted from Wagner et al. 2016, *J. Neuro*

Cortical IC Clusters



Hypotheses for Power Spectral Density

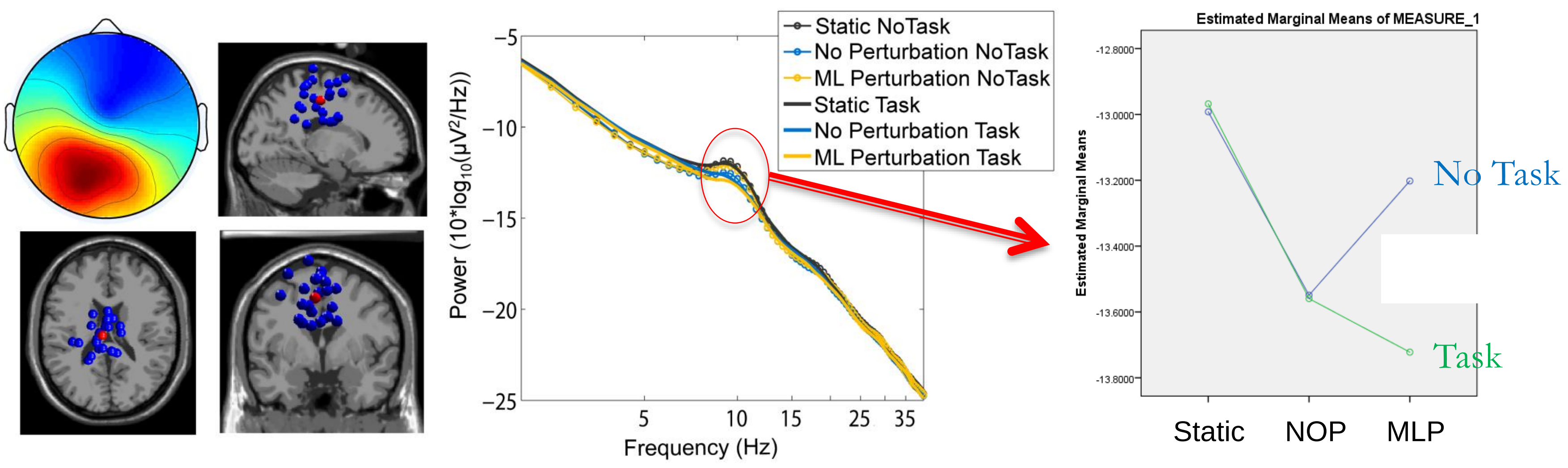
1. Power (amplitude) reduction or desynchronization, in 8-30Hz -> cortical excitability before and during movements
   - Hypothesis: decreased mu and beta power with increased sensory load (optic flow vs. static)

2. Visual processing leads to reduced alpha power over occipital regions
   - Hypothesis: Sensory load and cognitive load (processing letters vs. not processing letters) will lead to decreased power in the alpha (8-14Hz) band over occipital regions

3. Increased alpha power over parietal regions is linked to attentional mechanisms to suppress task-irrelevant information
   - Hypothesis: sensory load, particularly unreliable visual scene motion (ML perturbations) will drive alpha power over parietal cortex

PSD: frontal (SMA & ACC) Clusters

Supplementary motor area (14 S, 23 ICs)



Malcolm, Foxe, Butler*, Molholm, DeSanctis (2018)

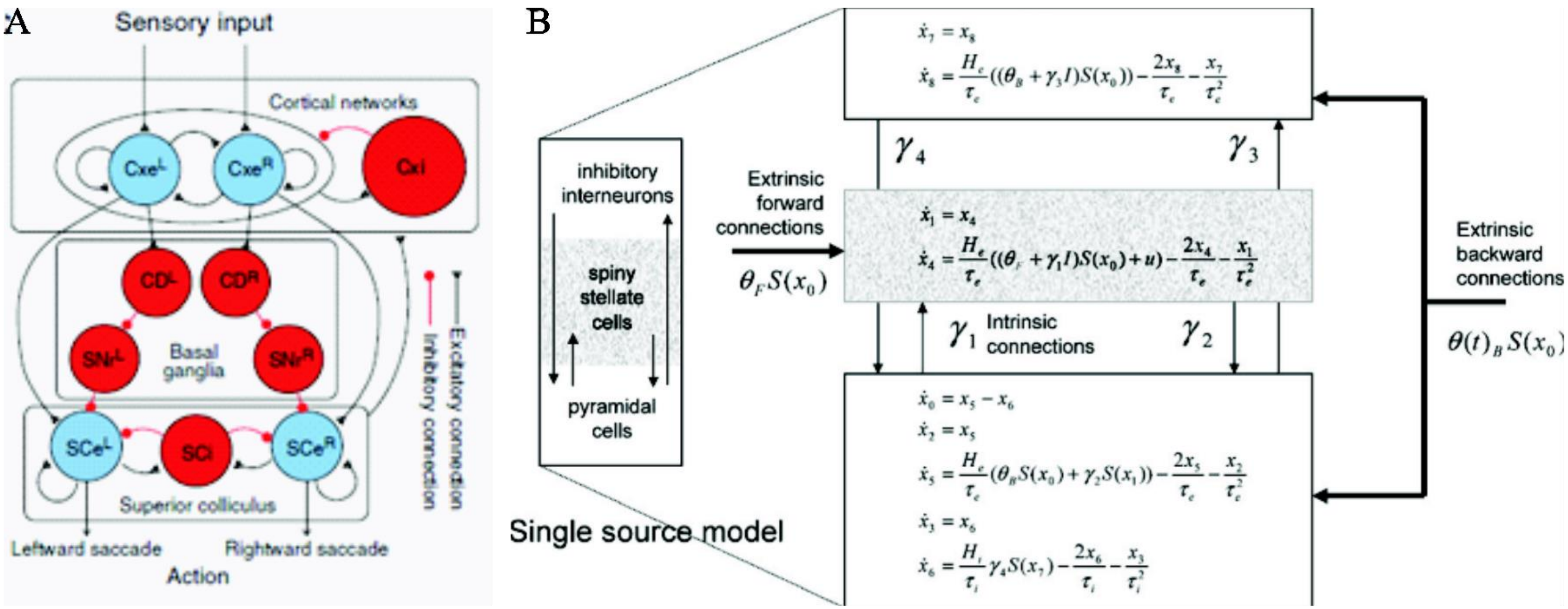
Summary IV

- One of the first studies that has attempted to understand cortical underpinnings of gait control under conflicting sensory demands
- ICA and clustering approach helped define a distributed network of sources responsive to sensory and cognitive load
- Optic flow induced changes in gait & posture may be used as a tool to assess cortical underpinnings of dynamic stability

Conclusion

- Simple models can explain and predict self-motion
- EEG can be collected during active and passive motion
  - Meaningful results that further our understanding of self-motion

Future Directions



Thank you

Albert Einstein College of Medicine
Adam Snyder
Brenda Malcolm
Pierefilipo DeSanctis
John Foxe

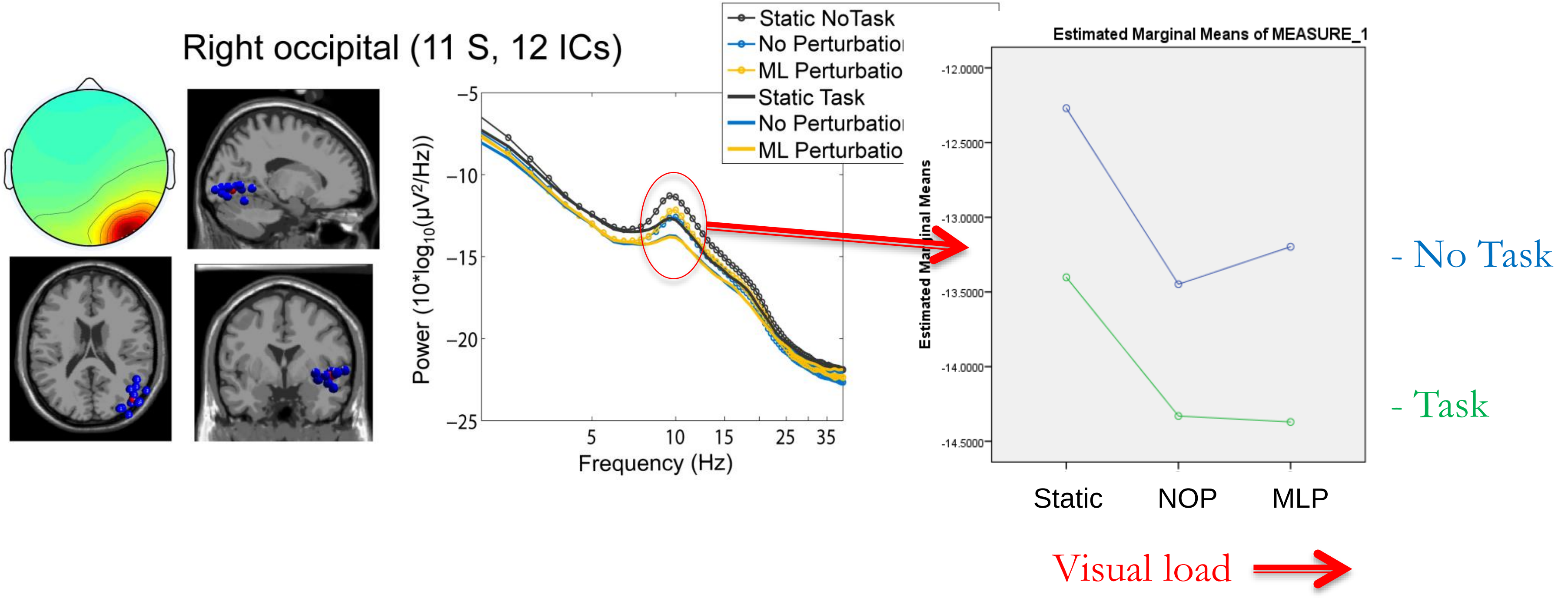
Trinity College Dublin
Hugh Nolan
Robert Whelan
Richard Reilly

Max Planck Institute for Biological Cybernetics
Jennifer Campos
Heinrich Bülthoff

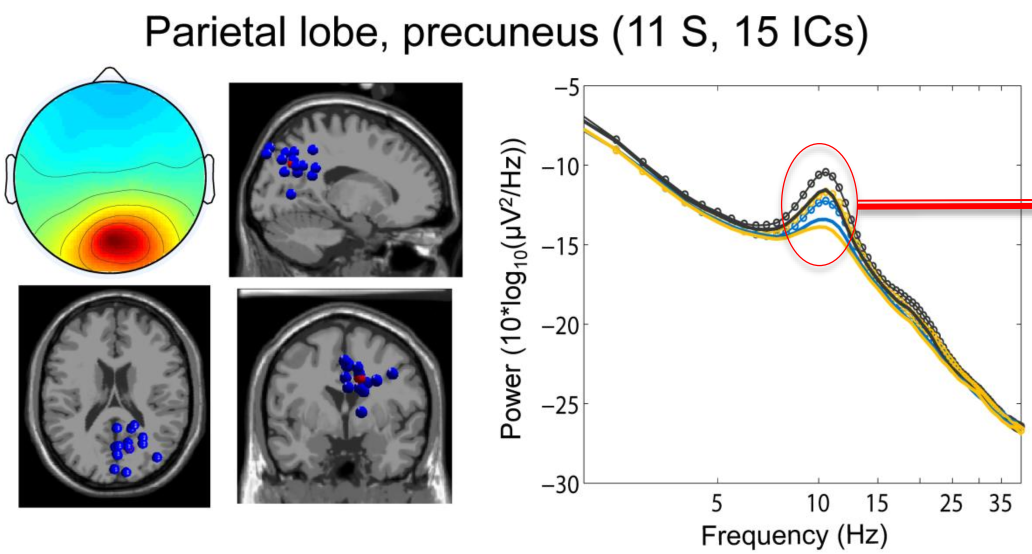
The Mater Misericordiae University Hospital
Conor Fearon
Timothy Lynch

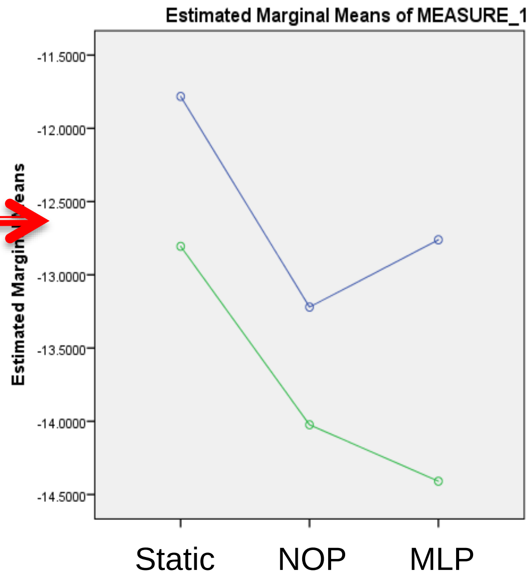
Any questions

PSD: Occipital alpha



PSD: Right parietal alpha





- No Task

- Task

Visual load →

Vestibular Oddball

- Vestibular Conditions
  - Diagonal Left Target
  - Diagonal Right Target

- Vestibular P3 paradigm
  - 80% Standard (320 sweeps)
  - 20% Target (80 sweeps)

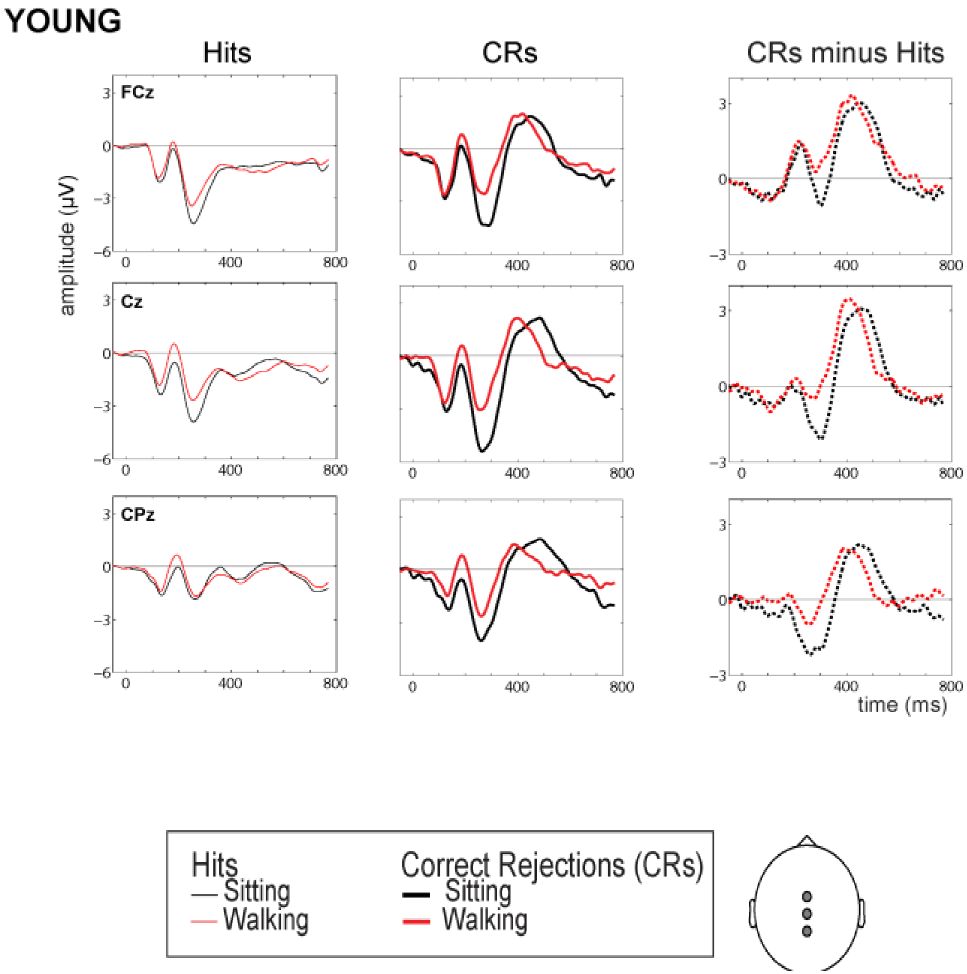
- 15 participants

- 128 scalp channels

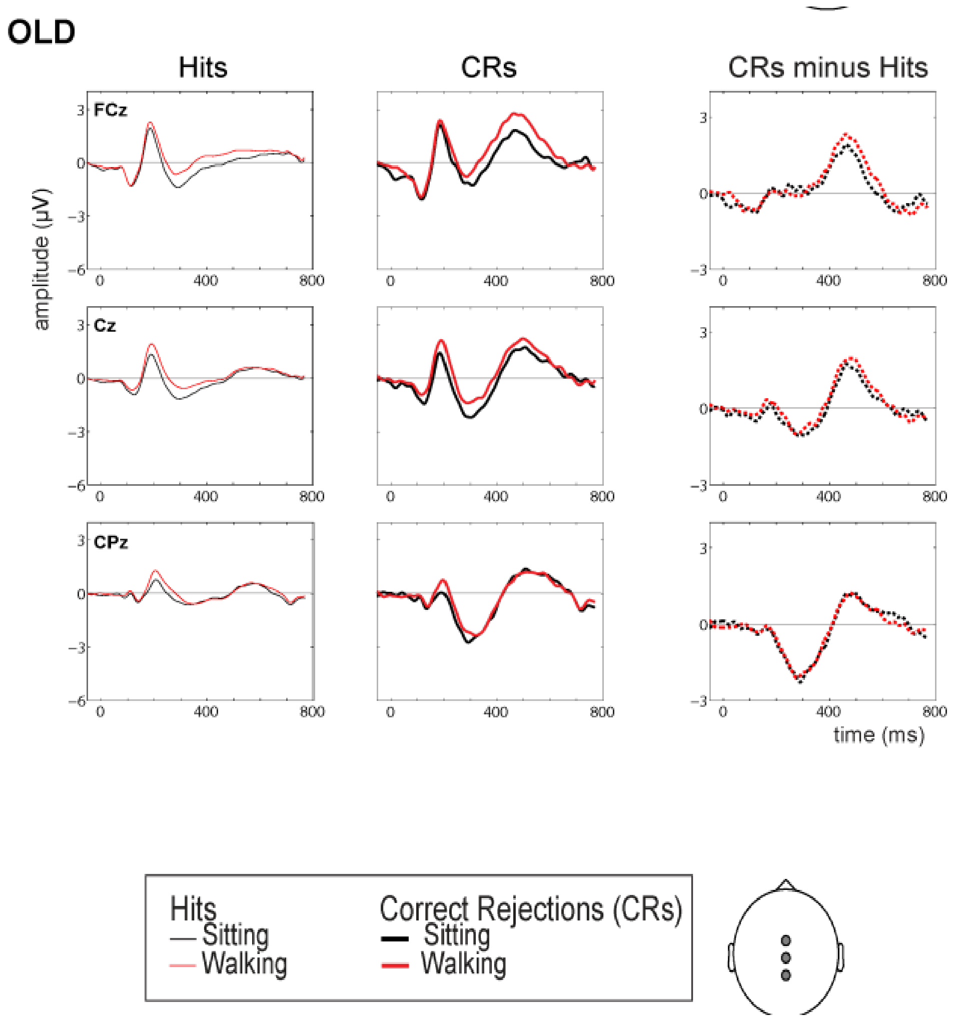
The aging brain shows less flexible reallocation of cognitive resources during dual-task walking: a mobile brain/body imaging (MoBI) study

Age	Young	Old
Range	21.8-36.1	57.7-71.0
Mean	27.2	63.9
SD	4.6	4.0
	N=18	N=18

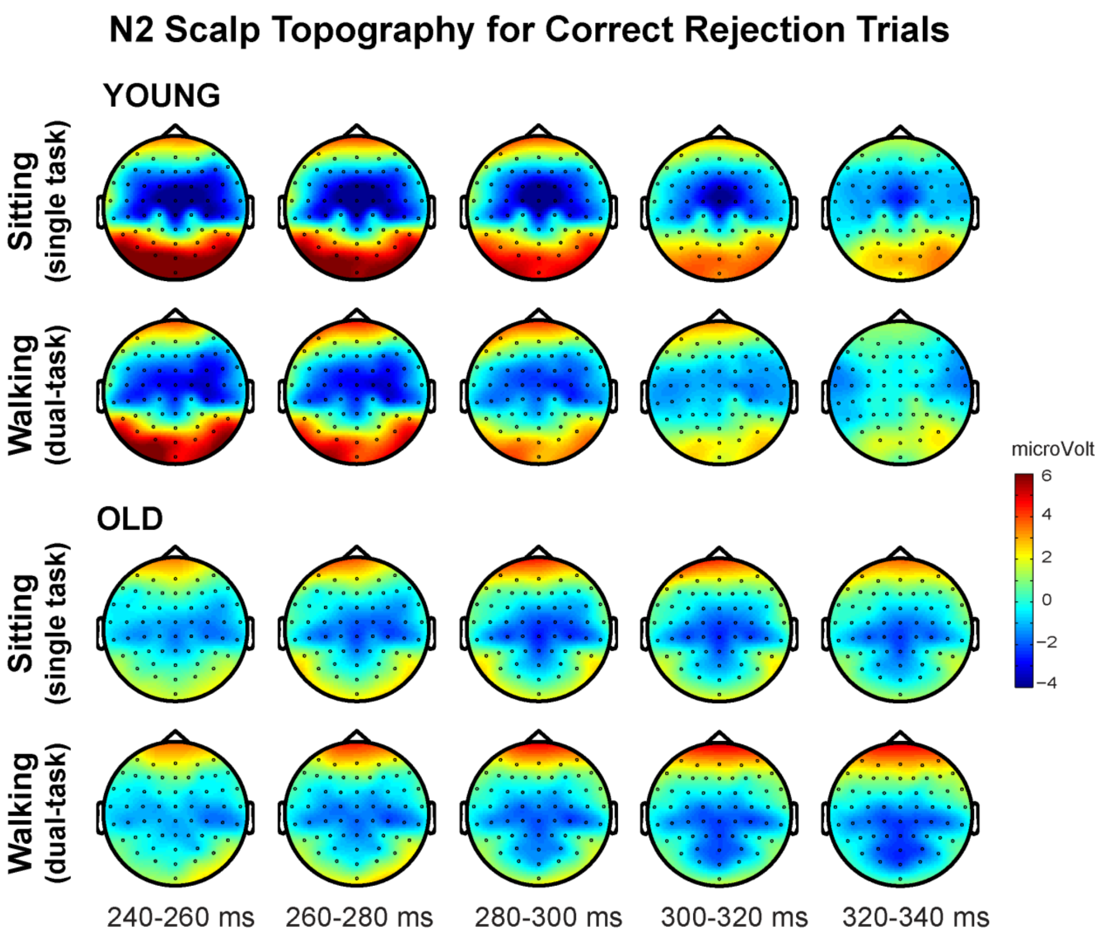
ERP - Young


YOUNG
Hits
CRs
CRs minus Hits
FCz
Cz
CPz
amplitude (μV)
time (ms)
Hits
Sitting
Walking
Correct Rejections (CRs)
Sitting
Walking

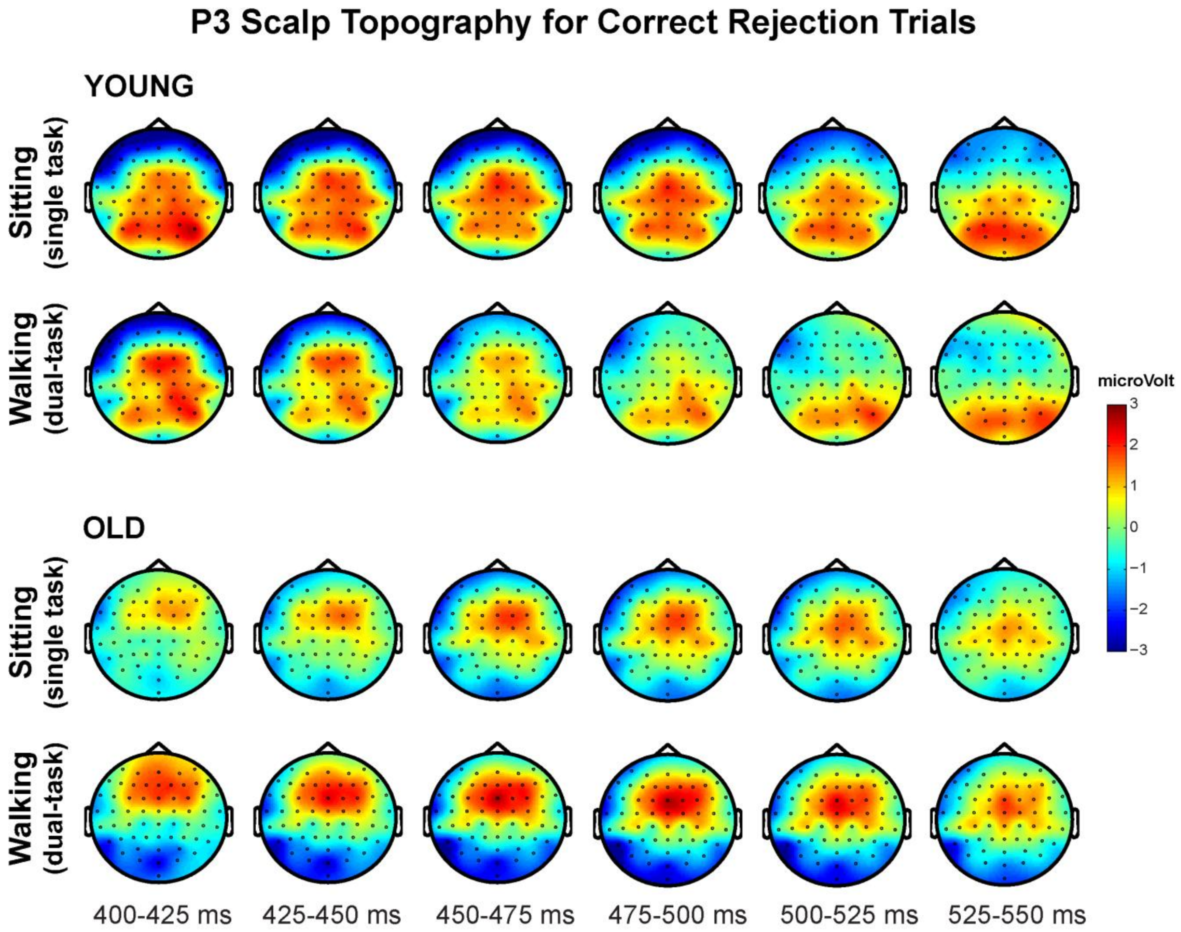
ERP - Old


OLD
Hits
CRs
CRs minus Hits
FCz
Cz
CPz
amplitude (µV)
time (ms)
Hits
Sitting
Walking
Correct Rejections (CRs)
Sitting
Walking

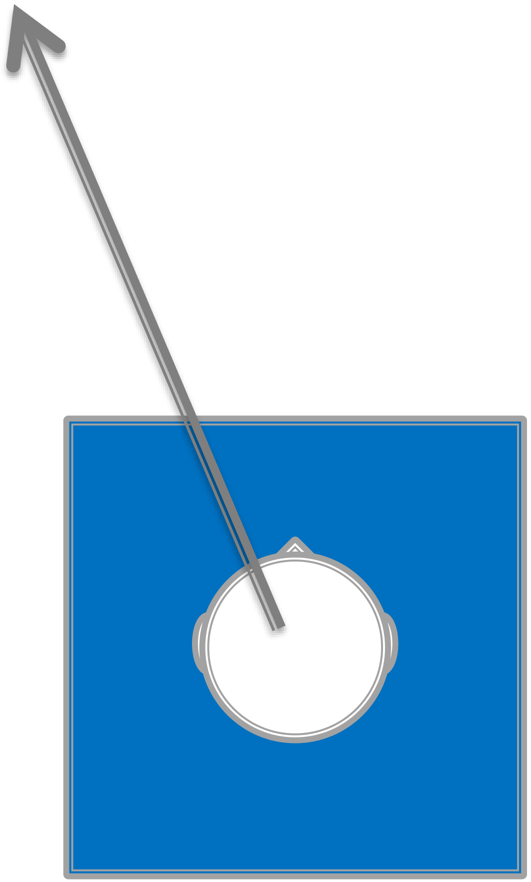
N2 topographical distribution



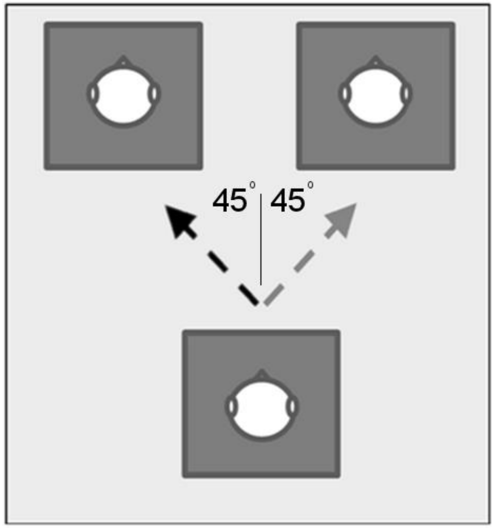
P3 topographical distribution

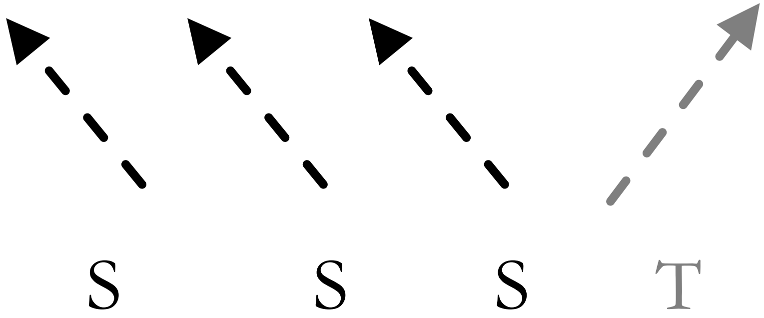


Vestibular Oddball



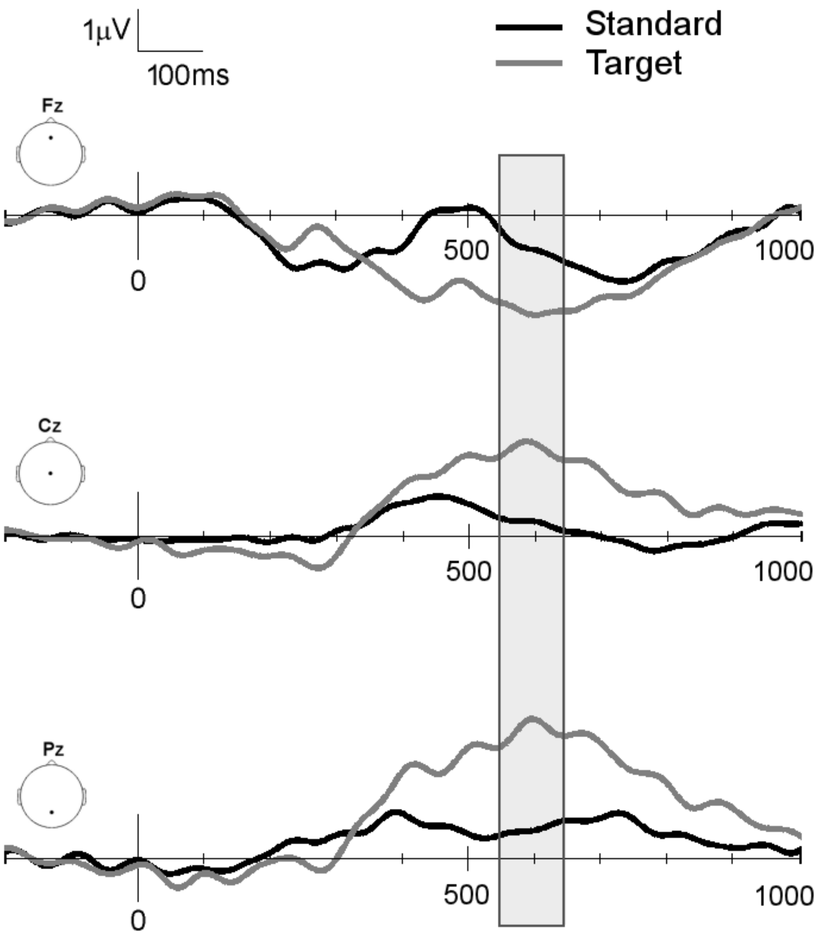
Procedure





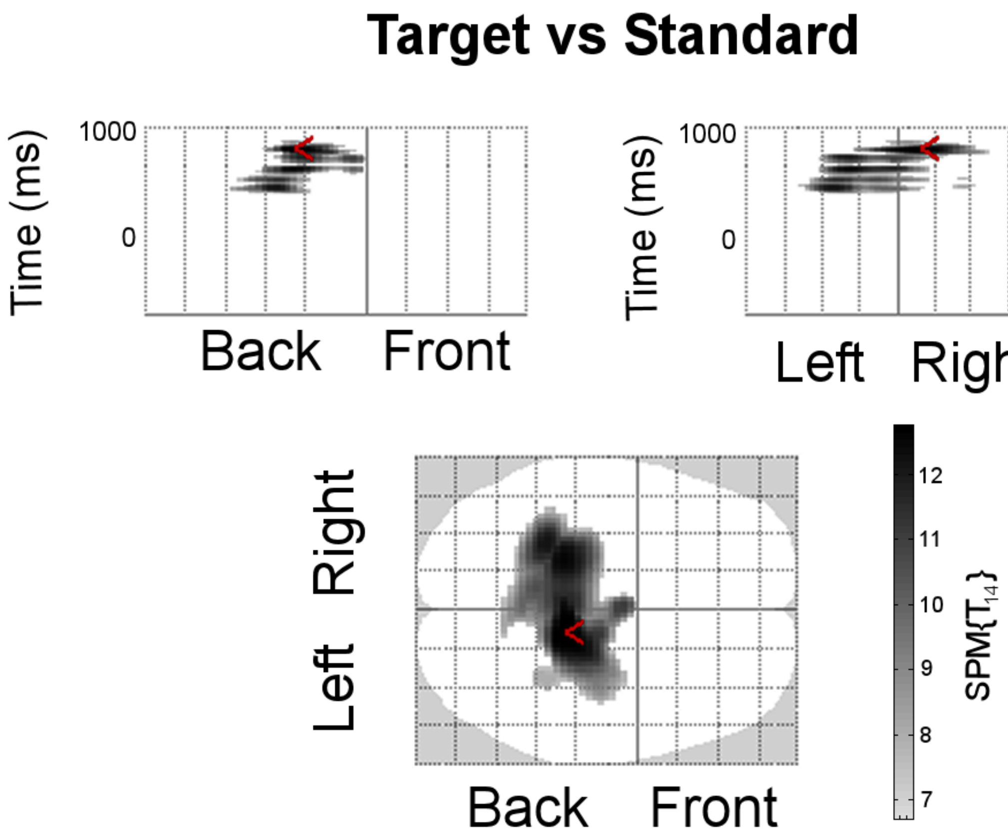
A neuronal marker for vestibular change detection

Results- Vestibular P3



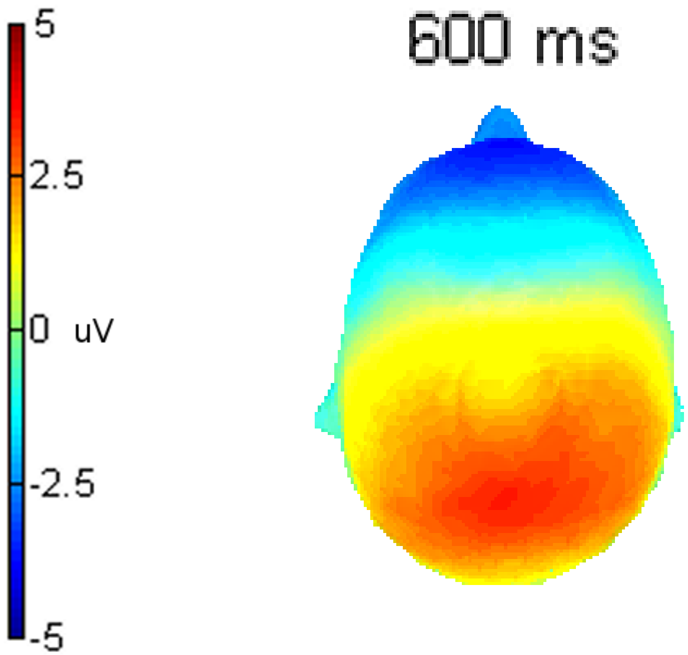
- Statistical difference between the standard and target

P3 distribution



Target topographic scalp distribution is similar to the typical P3 distribution for other sensory modalities

Scalp Distribution

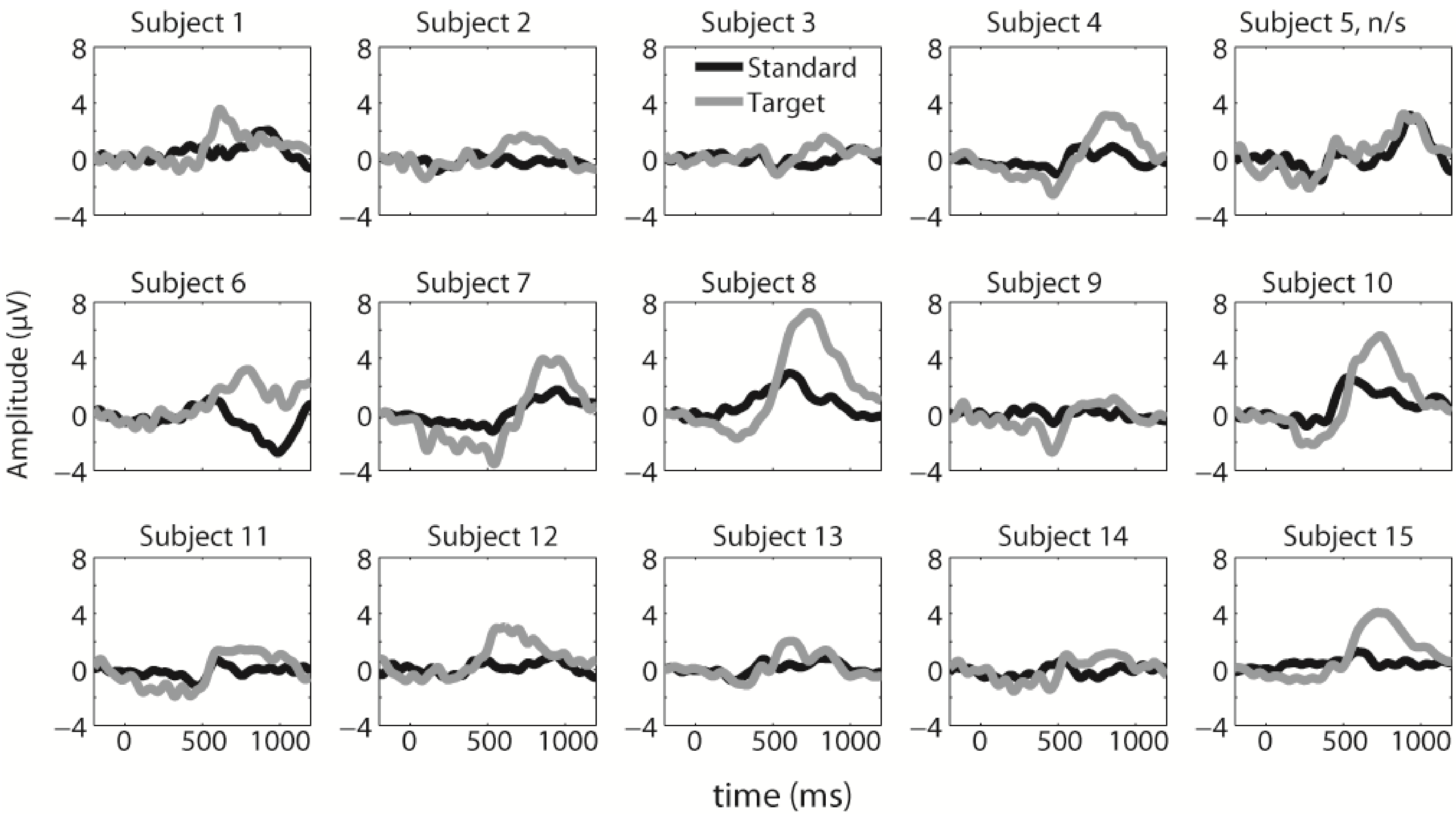


- Target topographic scalp distribution is similar to the typical P3 distribution for other sensory modalities

Individual Participant Analysis

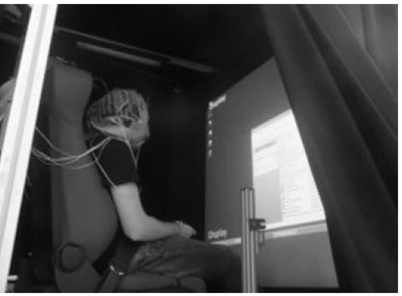
BOOTSTRAP

Individual Participant data



14 of 15 participants exhibited a P3

Summary II

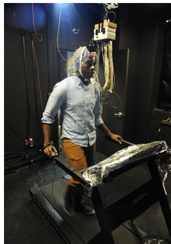


- This is the first time vestibular heading change detection has been shown to elicit a P3 component.

Nolan, **Butler**, Whelan, Foxe, Bulthoff, Reilly (2012)

Response Inhibition Task

- Task
  - Go/Nogo Response Inhibition Task
  - NoGo: repetition of the same picture
  - Stimulus presentation rate 1/per sec
  - Go/Nogo = 80/20%
- Conditions
  - Sitting
  - Walking Slow (2.4 km/h)
  - Walking Fast (5 km/h)



Methods

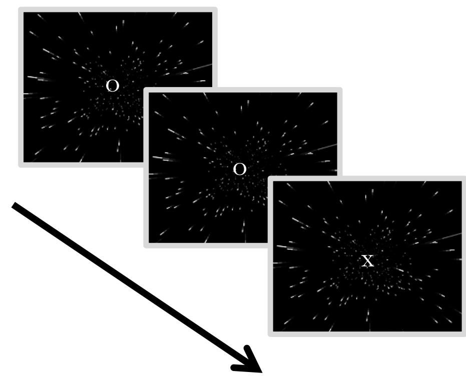
Participants

- Young Adults (n=16) mean age = 25.6 years
- Average walking speed: 3.9 km/hr (range: 3.2 – 4.5)

6 Experimental Conditions

- Task Load (2) x Optic Flow (3)
- 3 blocks of each condition

- Task:
  - Go/No-Go probability = 80%/20%
  - Letter presentation = 400ms
  - Random SOA : 600-800ms
- Optic Flow
  - static (control condition?)
  - steady/no perturbation
  - mediolateral perturbations



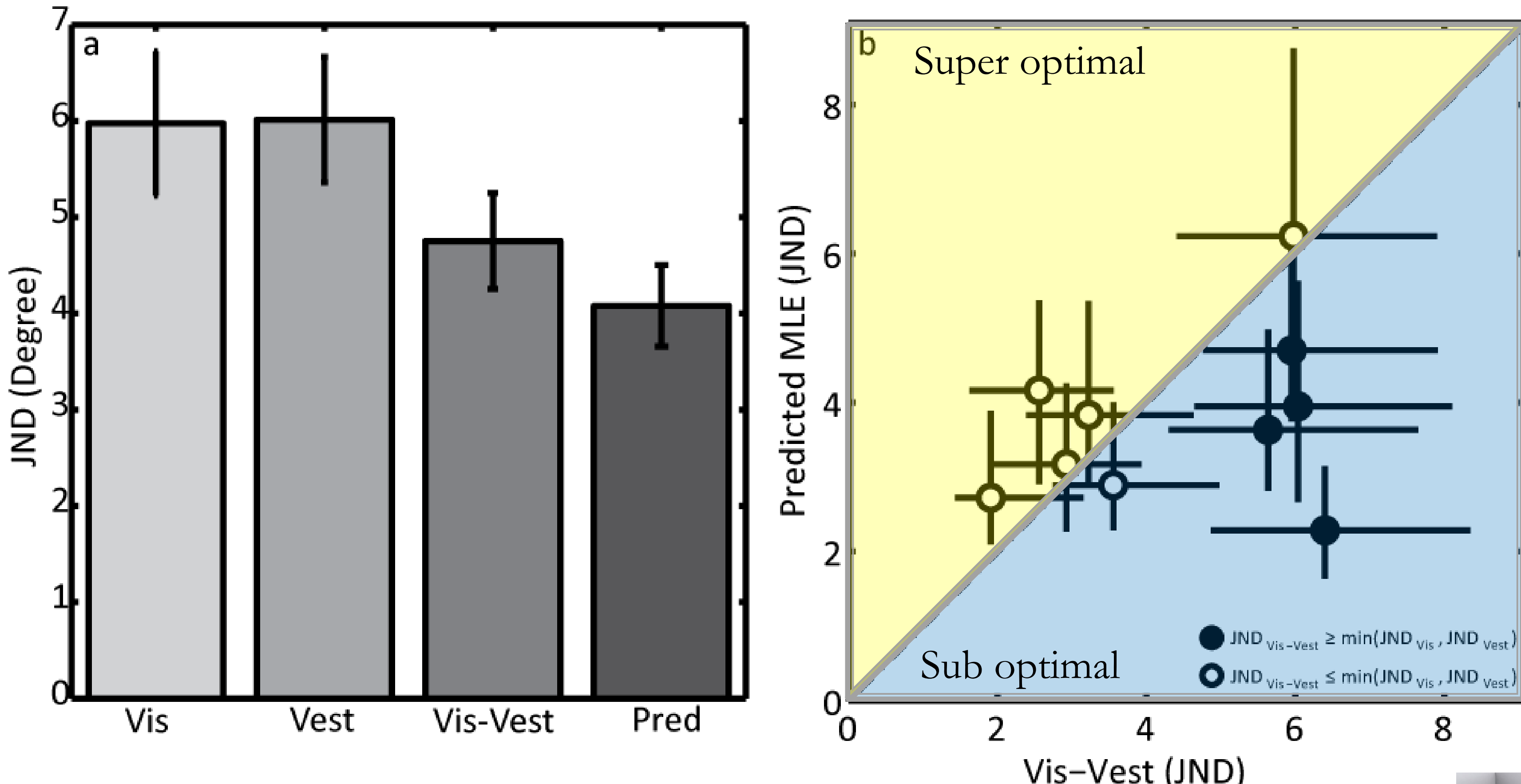
Cognitive Load	**Sensory Load: Optic Flow Perturbation** (relative to walking speed/direction)		
	Static/No-Task	Congruent/No-Task	Incongruent/No-Task
	Static-Task	Congruent/Task	Incongruent/Task

Summary IV

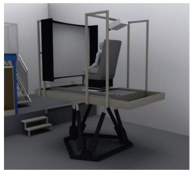
- Younger adults adjust gait and cognitive control when presented with a dual task situation
- Healthy older adults show a lack of flexibility, both in terms of adjusting physical behavior and in reconfiguring cognitive control mechanisms at the neural level.

Binocular Condition

Binocular Condition

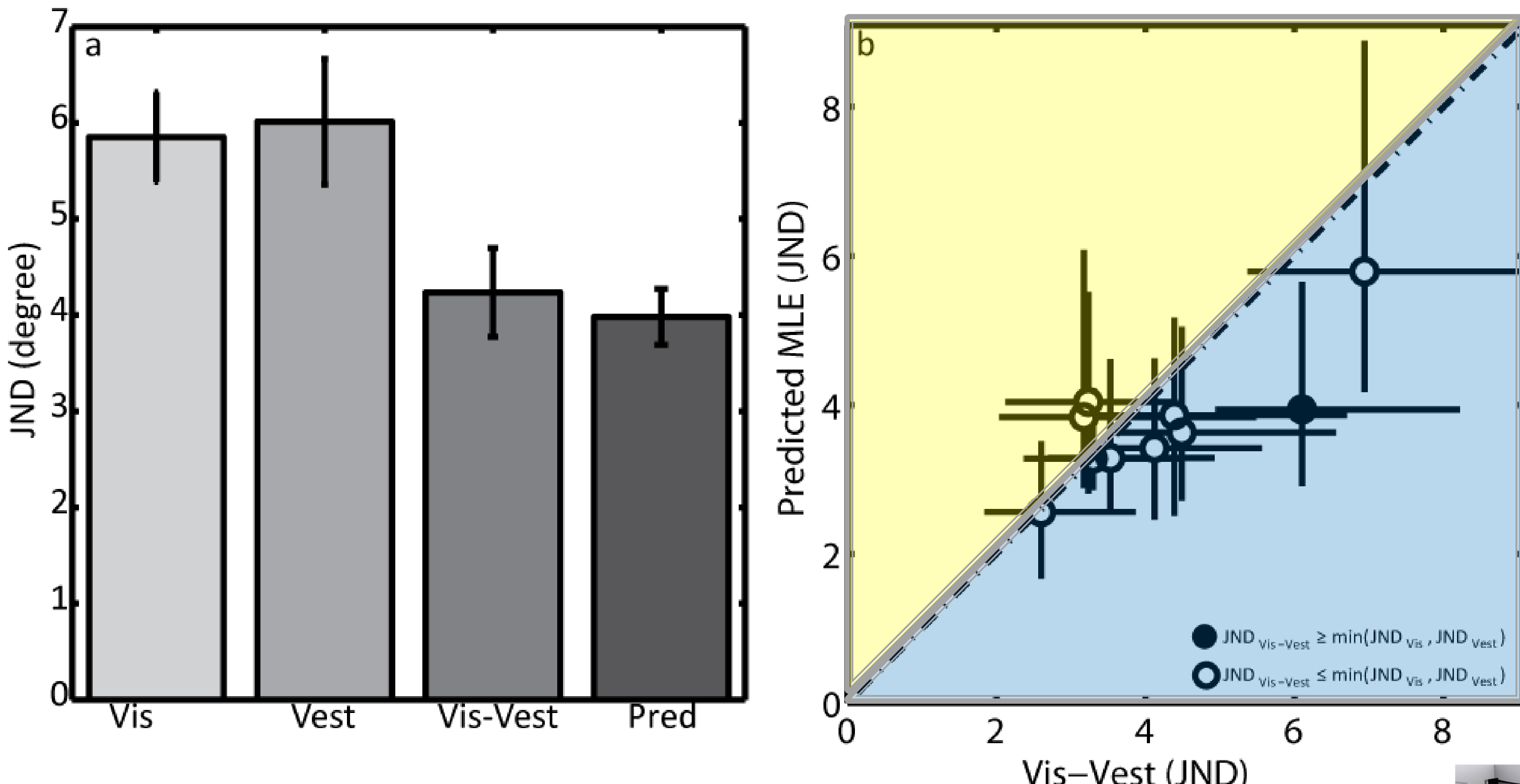


6 of the 10 exhibit optimal combination of sense



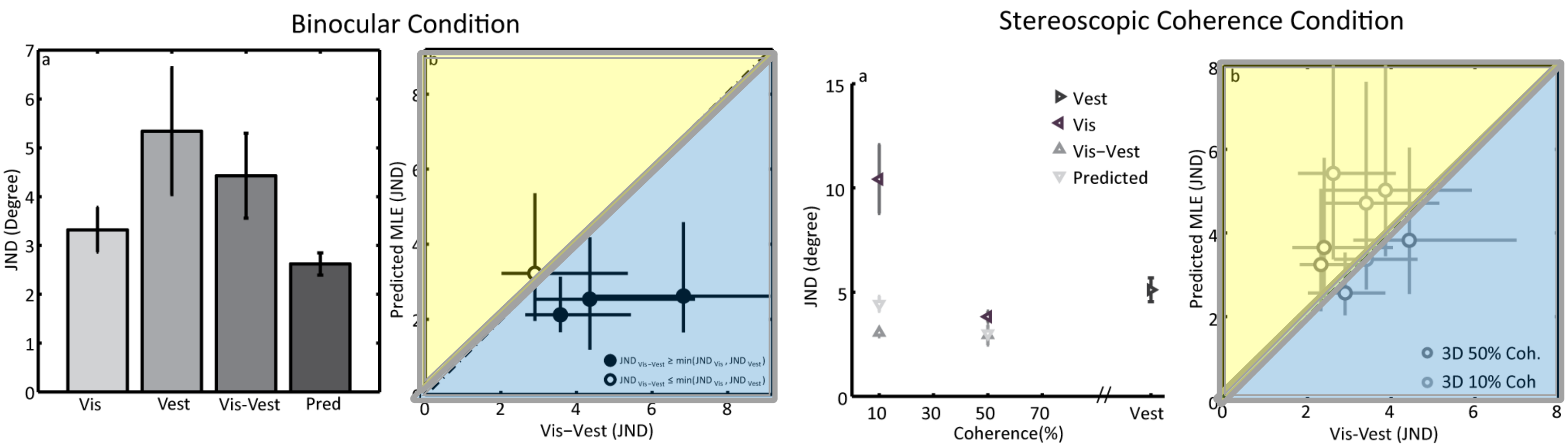
Stereoscopic Condition

Stereoscopic Condition

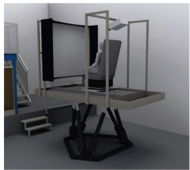


9 of the 10 exhibit optimal combination of sense

Reproducible nature of result



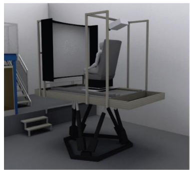
A subset of the original participants were re-run and exhibited identical results



Summary

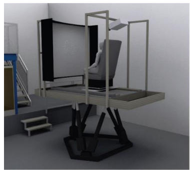
- The presence/absence of stereoscopic visual information can impact the extent to which visual and vestibular cues are integrated during heading perception.
- This was reproducible within participants

J. S. Butler et al. / *Seeing and Perceiving 24 (2011) 453–470*

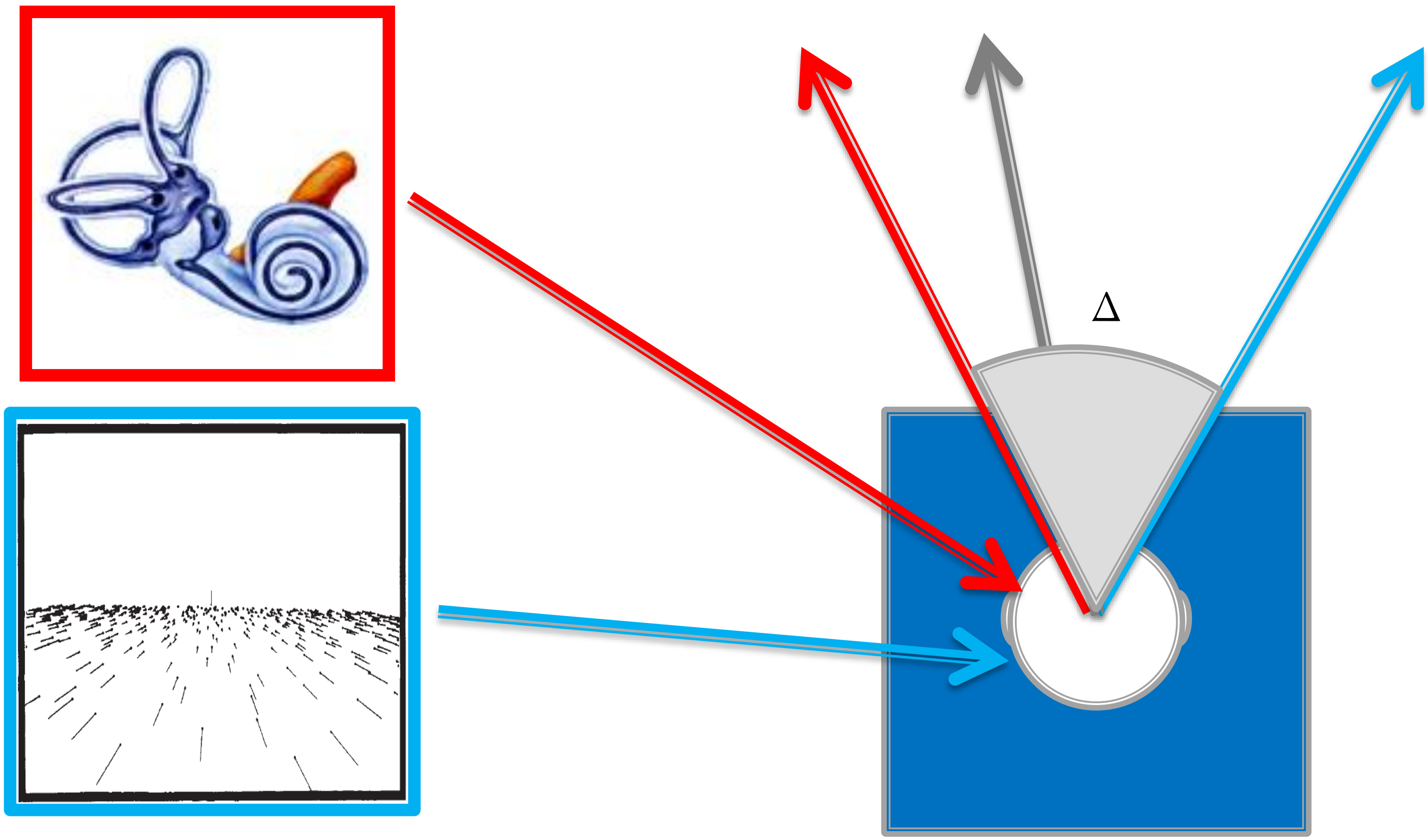


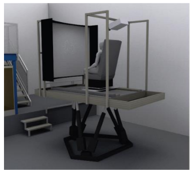
Talk Overview

- Passive Heading detection
  1. The role of Stereo cues
  2. Conflict of information
  3. Neural correlates of heading detection change
- Active tasks
  4. Walking
  5. Neural recordings while walking



Visual-Vestibular Integration for Heading (conflict)

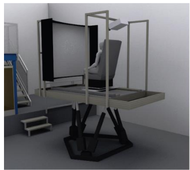




Why introduce a conflict?

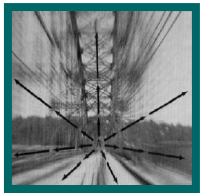
- By introducing a conflict we can see if there is a breakdown of the combination of sense

- We can calculate the weights given to each cue

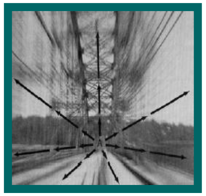


The logic of conflicts

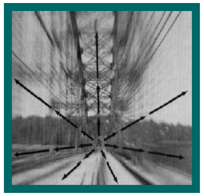
Equally weighted

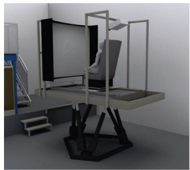


Vestibular weighted more

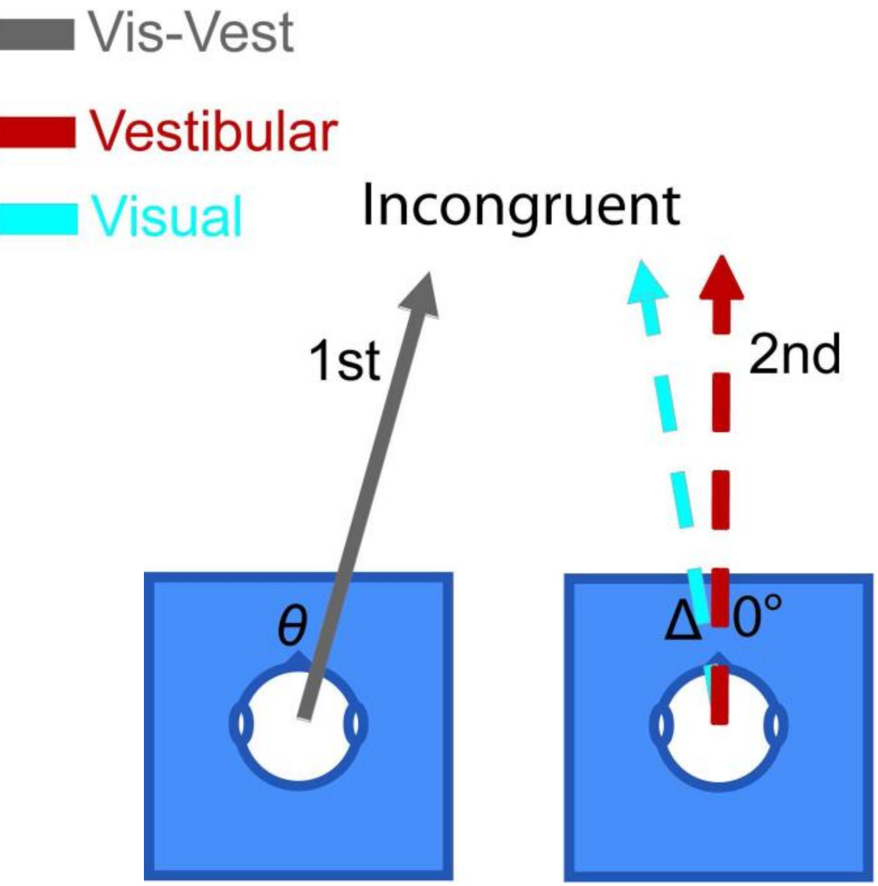


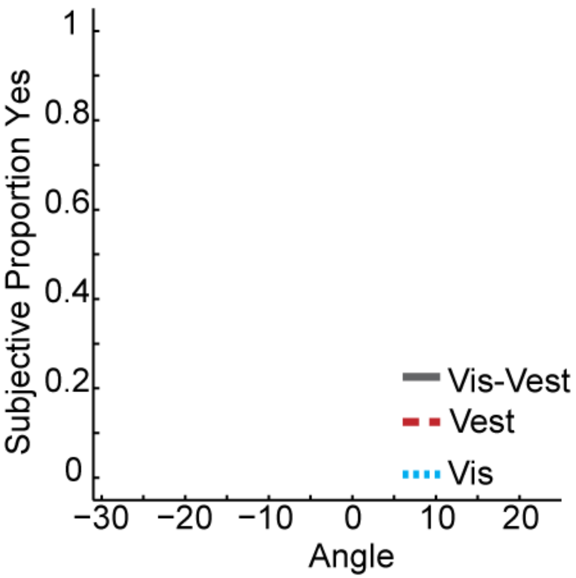
Vision weighted more

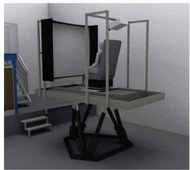




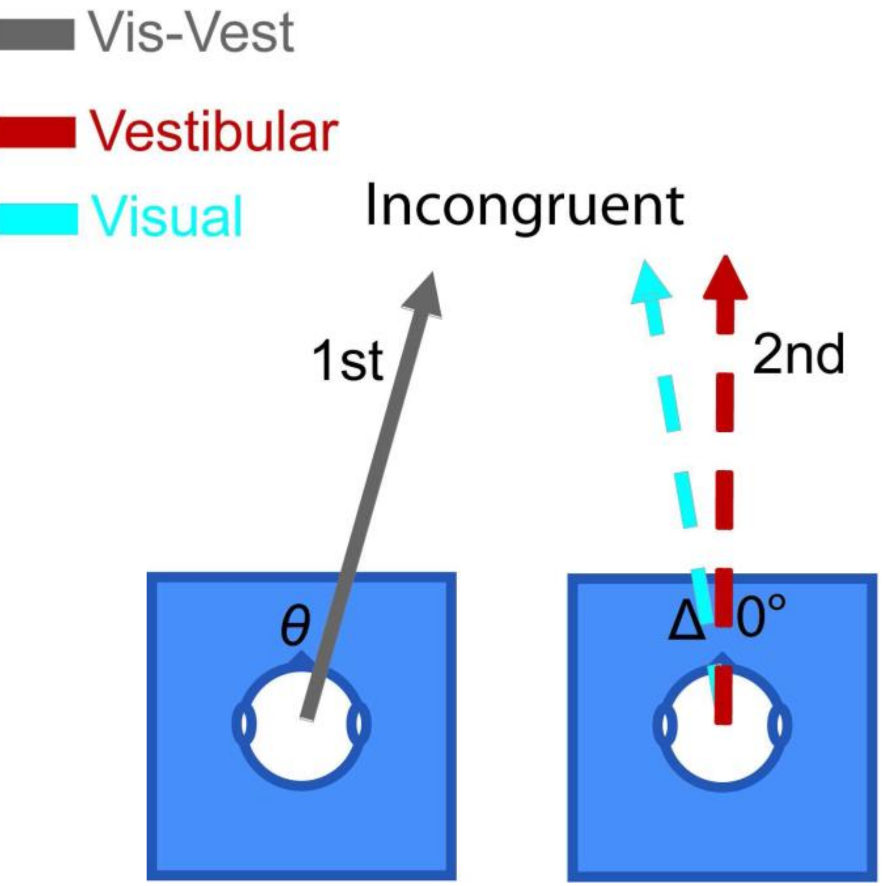
Individual participant analysis

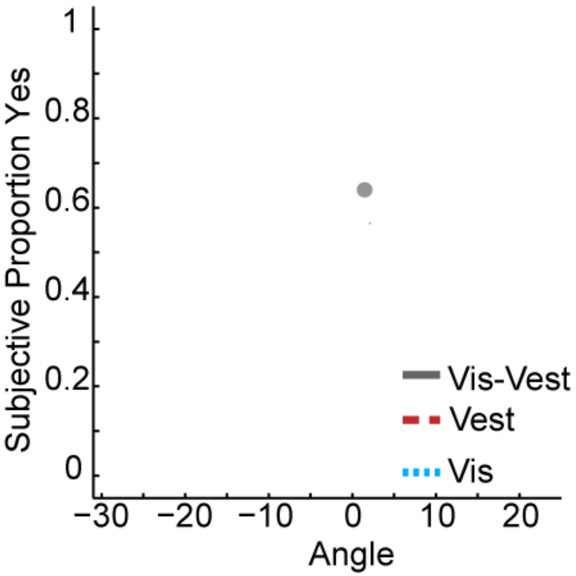


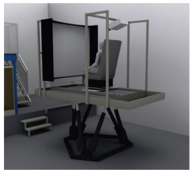




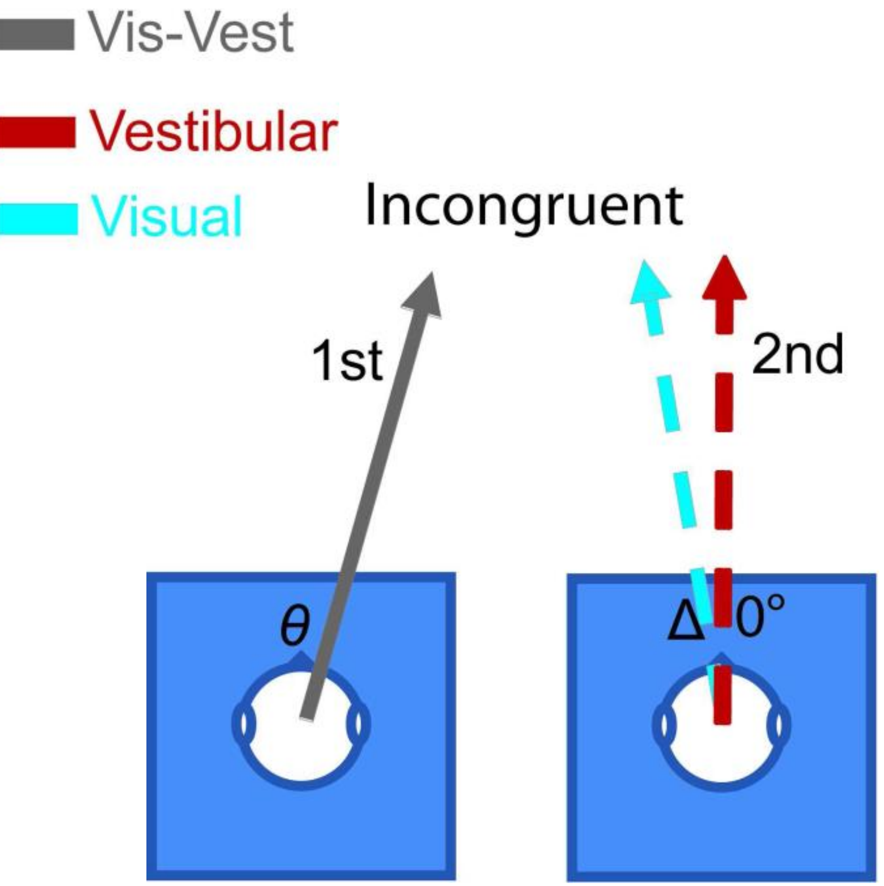
Individual participant analysis

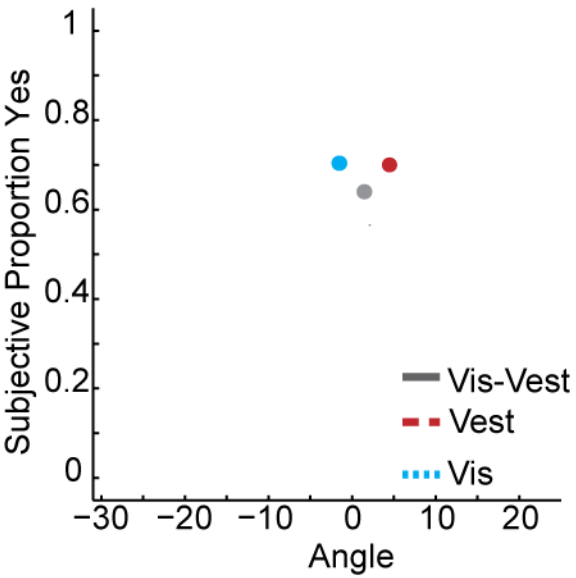


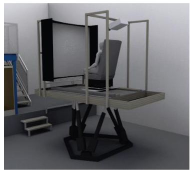




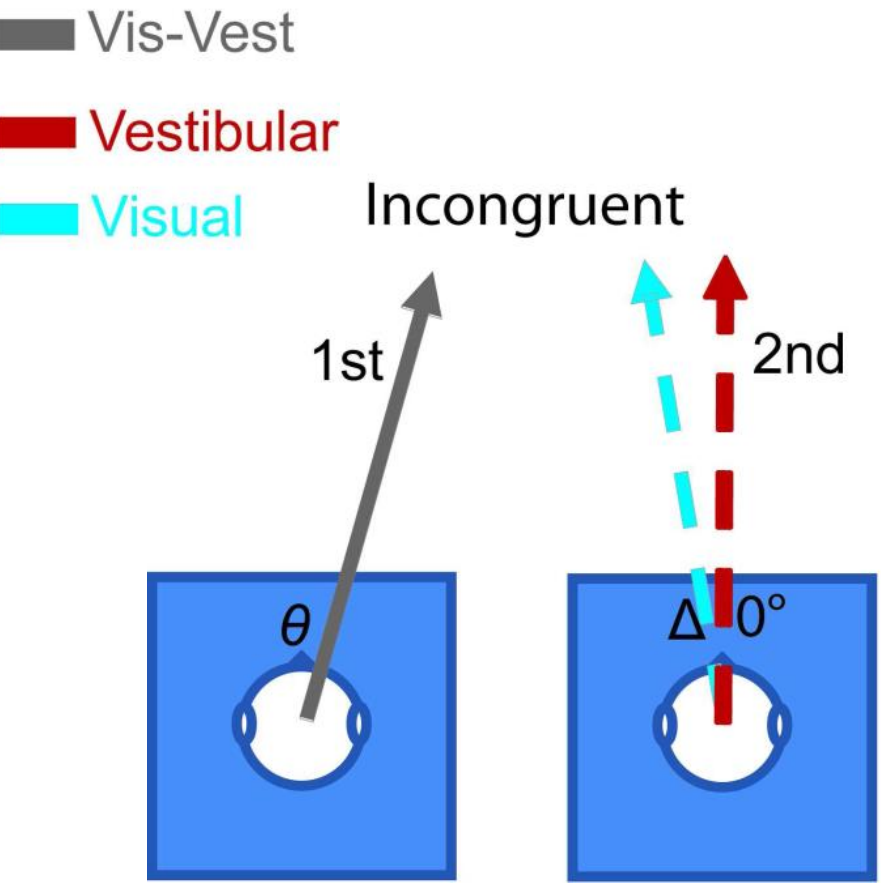
Individual participant analysis

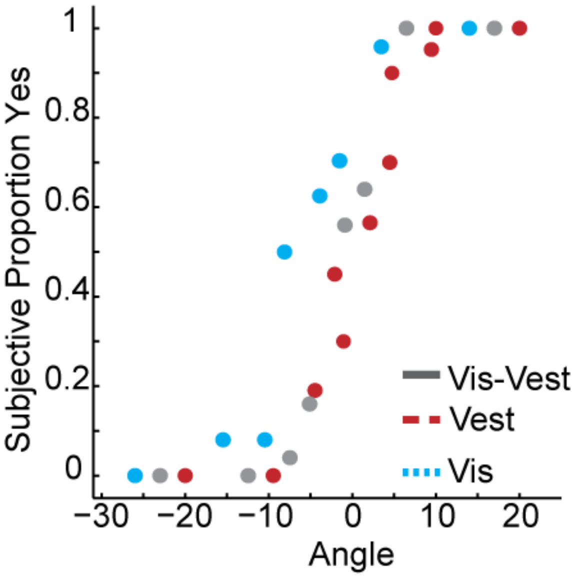


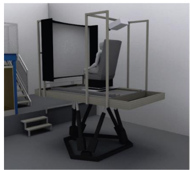




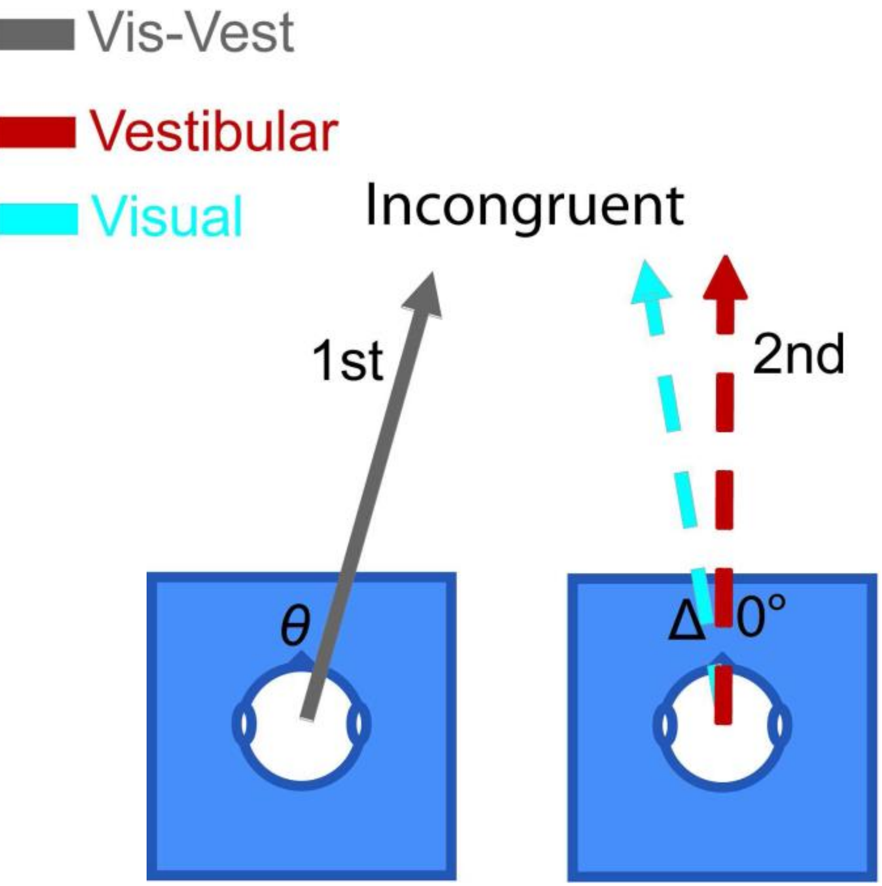
Individual participant analysis

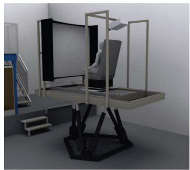






Individual participant analysis





Maximum Likelihood Estimation

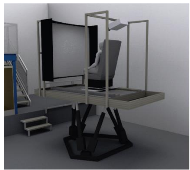
$$\widehat{S}_{Vis-Vest} = w_{Vis}\hat{S}_{Vis} + w_{Vest}\hat{S}_{Vest}$$

Observed

$$w_{Vis} = \frac{PSE_{Vis-Vest} - PSE_{Vest}}{PSE_{Vis} - PSE_{Vest}} \qquad w = \frac{1/\sigma^2_{Vis}}{\frac{1}{\sigma^2_{Vis}} + \frac{1}{\sigma^2_{Body}}}$$

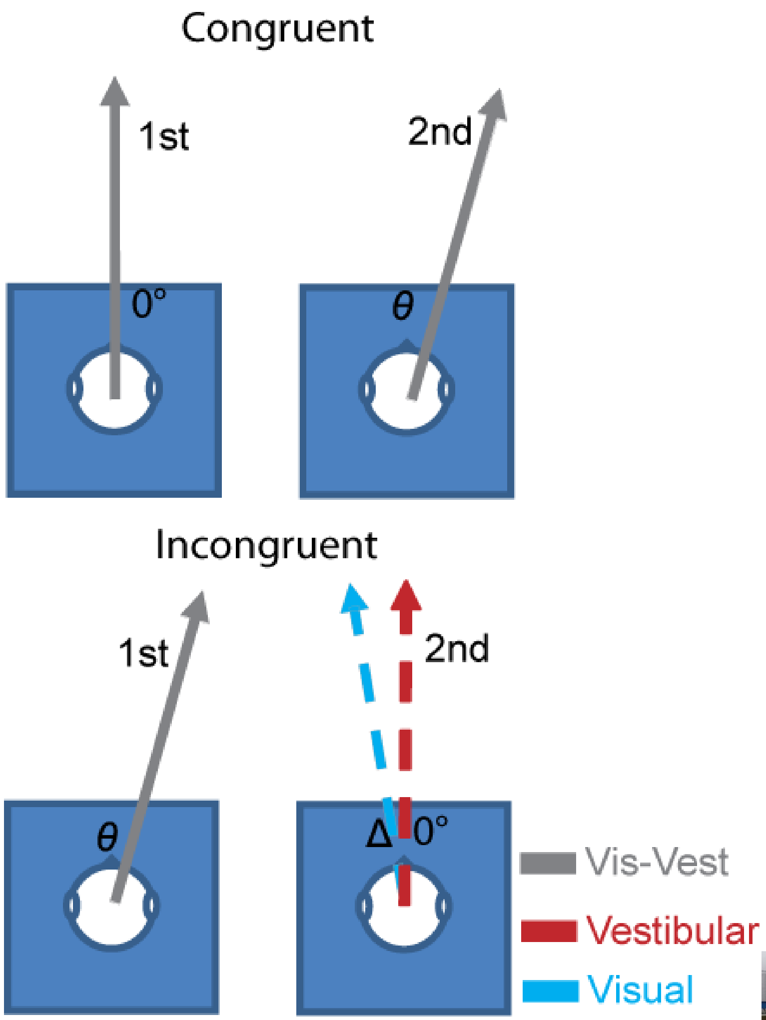
Predicted

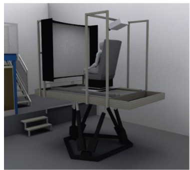
$$\hat{w}_{Vis} = \frac{1/\,JND^2_{Vis}}{1/\,JND^2_{Vis} + 1/\,JND^2_{Vest}}$$



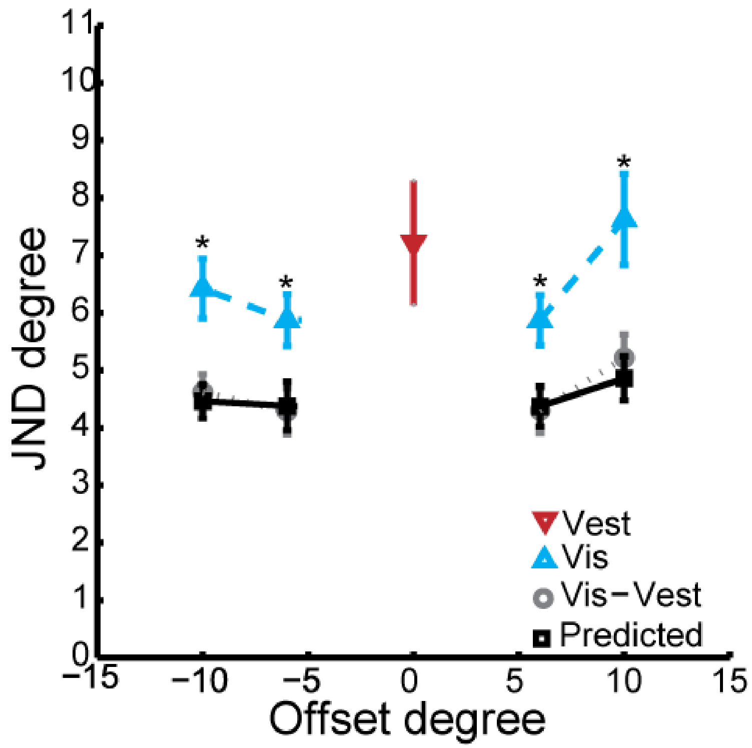
Spatial Conflict

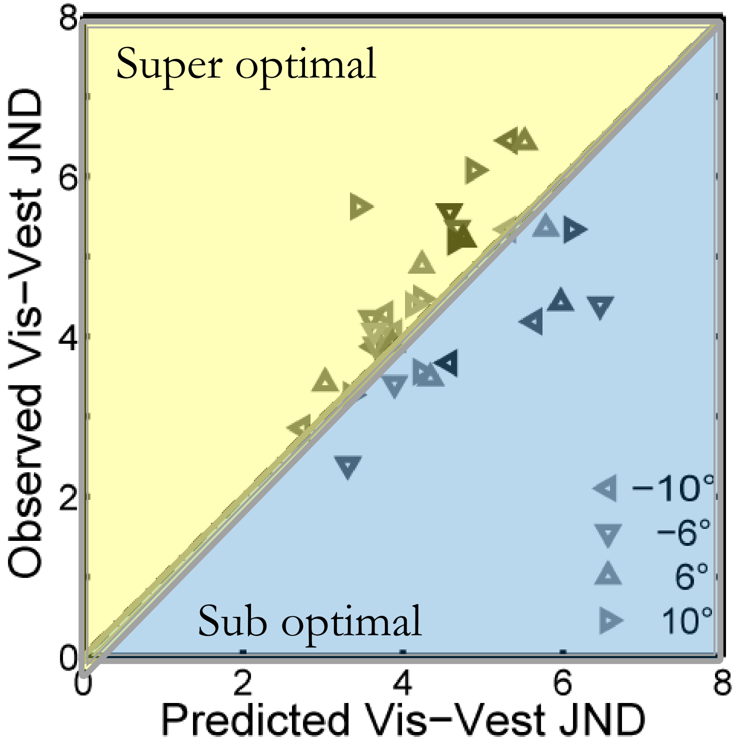
- Conditions
  - 1 Vestibular alone
    - One Standard
    - $\Theta=0°$
  - 4 Visual alone
    - Four standards
    - $\Theta=\pm 6°, \pm 10°$
  - 4 Visual-vestibular
    - One Standard
    - $\Theta=0°$
    - Four Offset
    - $\Delta=\pm 6°, \pm 10°$



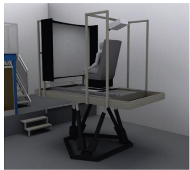


Optimal reduction in variance

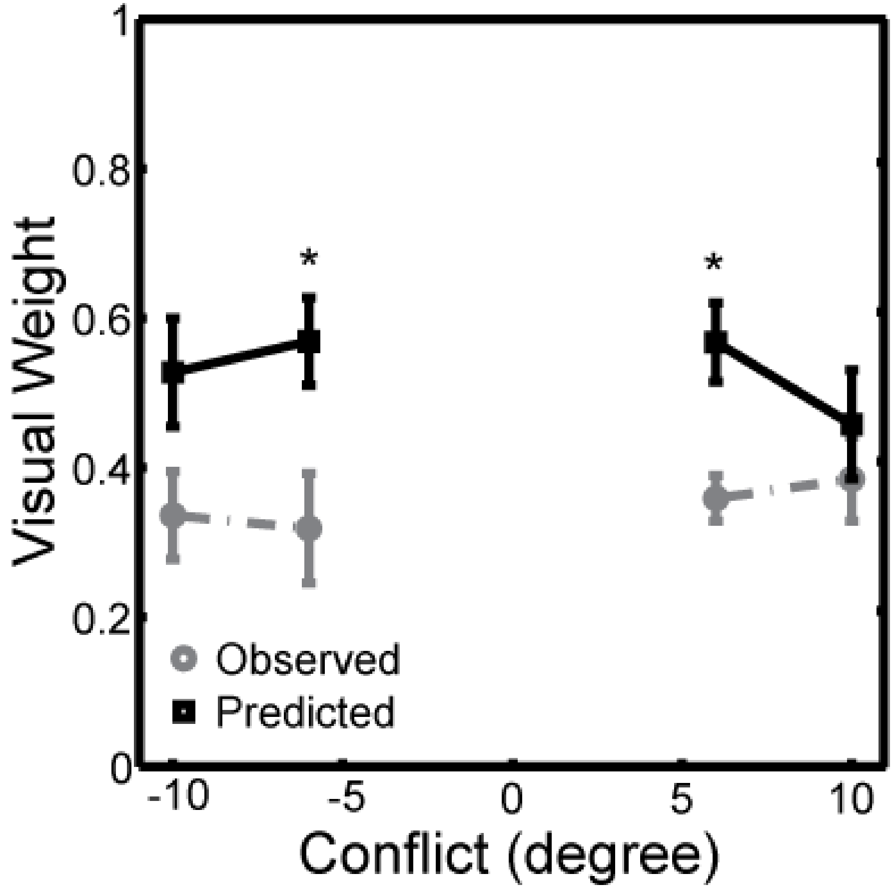




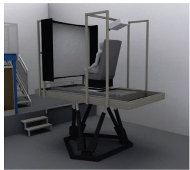
The combination of visual and vestibular cues observe an optimal rule of integration



Weights



The weights are biased towards the vestibular cue

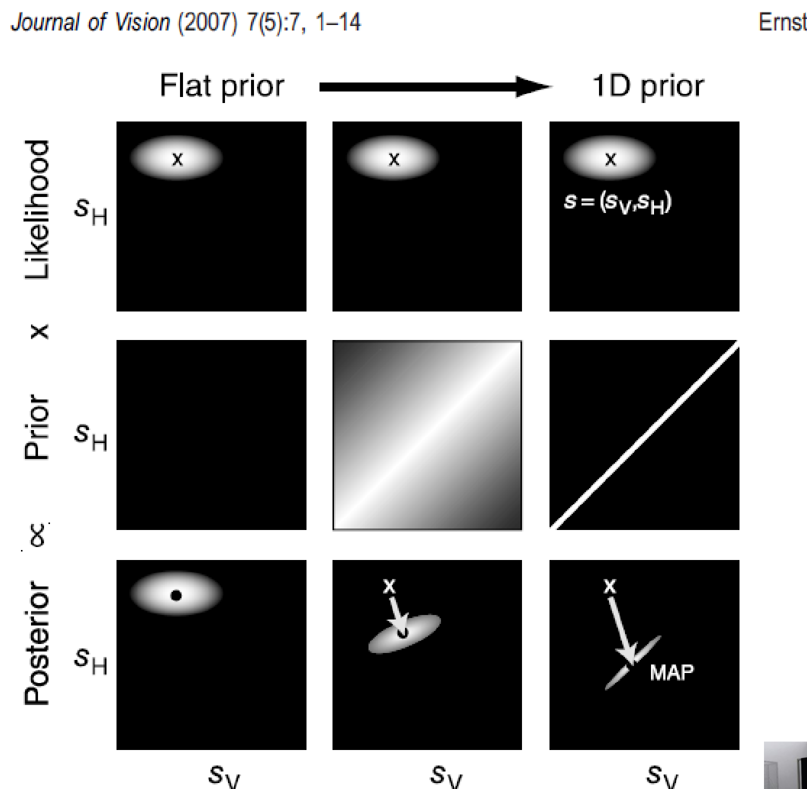


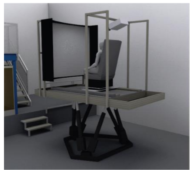
Introduction of a Prior

$$\widehat{S}_{Vis-Vest} = w_{Vis}\hat{S}_{Vis} + w_{Vest}\hat{S}_{Vest} + w_{Prior}\hat{S}_{Prior}$$

$$JND^2_{Vis-Vest} = \frac{1}{1/JND^2_{Vis} + 1/JND^2_{Vest} + 1/JND^2_{Prior}}$$

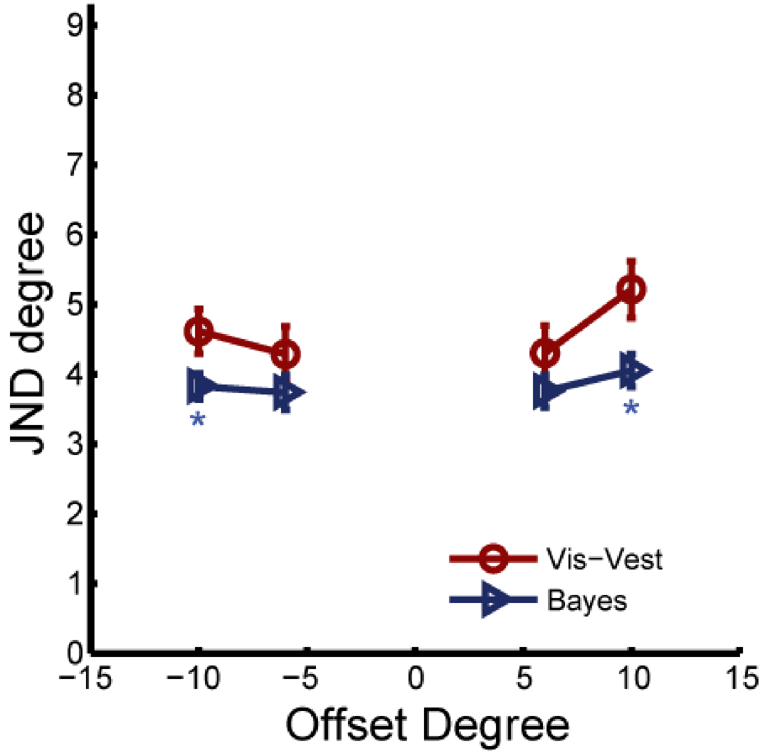
$$w_{Vis} = \frac{1/JND^2_{Vis}}{1/JND^2_{Vis} + 1/JND^2_{Vest} + 1/JND^2_{Prior}}$$



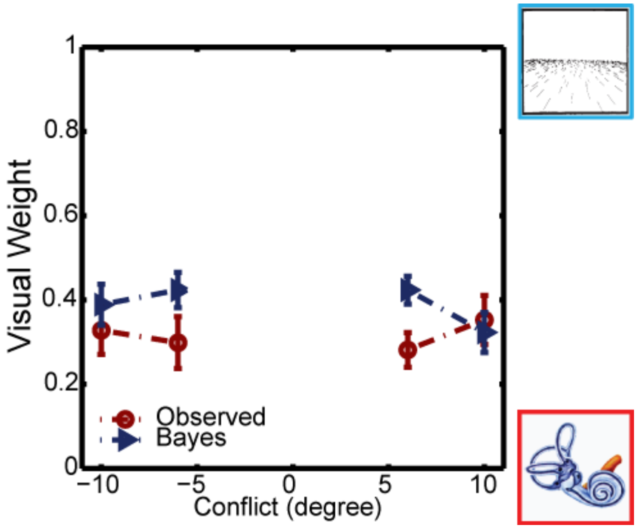


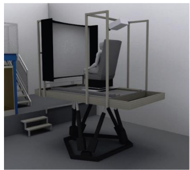
Bayesian Model

ACCURACY



WEIGHTS

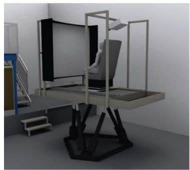




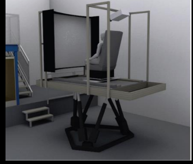
Summary results

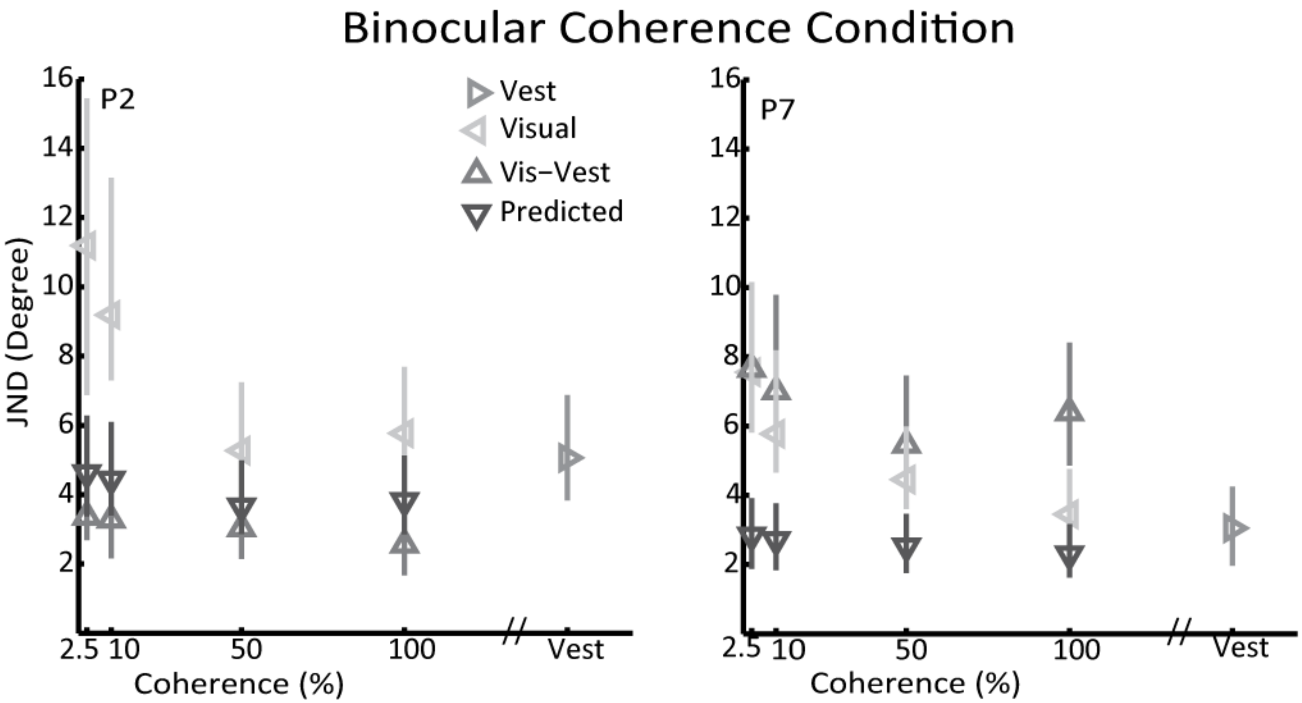
- Participants exhibited a statistically optimal reduction of variance under combined cue conditions.
- Performances in the unimodal conditions did not predict the weights in the combined cue conditions.
- Therefore, we conclude that visual and vestibular cue combination is not predicted solely by the reliability of each individual cue but rather, there is a prior which leads to a higher weighting of vestibular information in this task.

Butler, Smith, Campos, & Bülthoff *Journal of Vision* (2010)

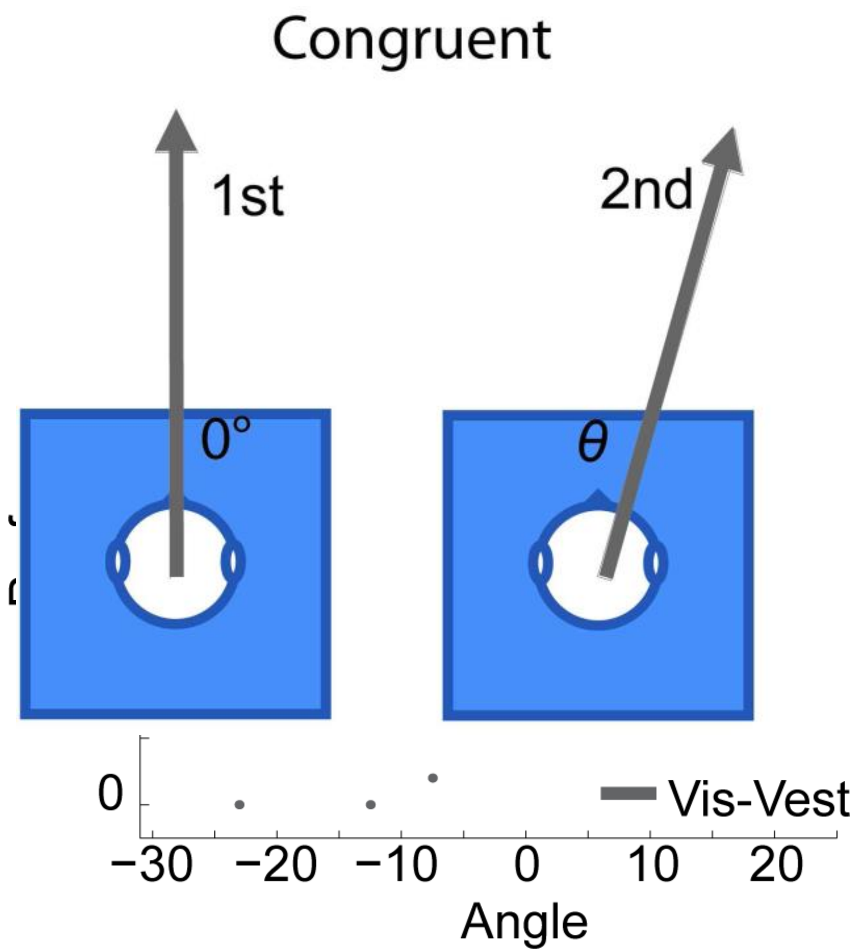


Reproducible nature of result

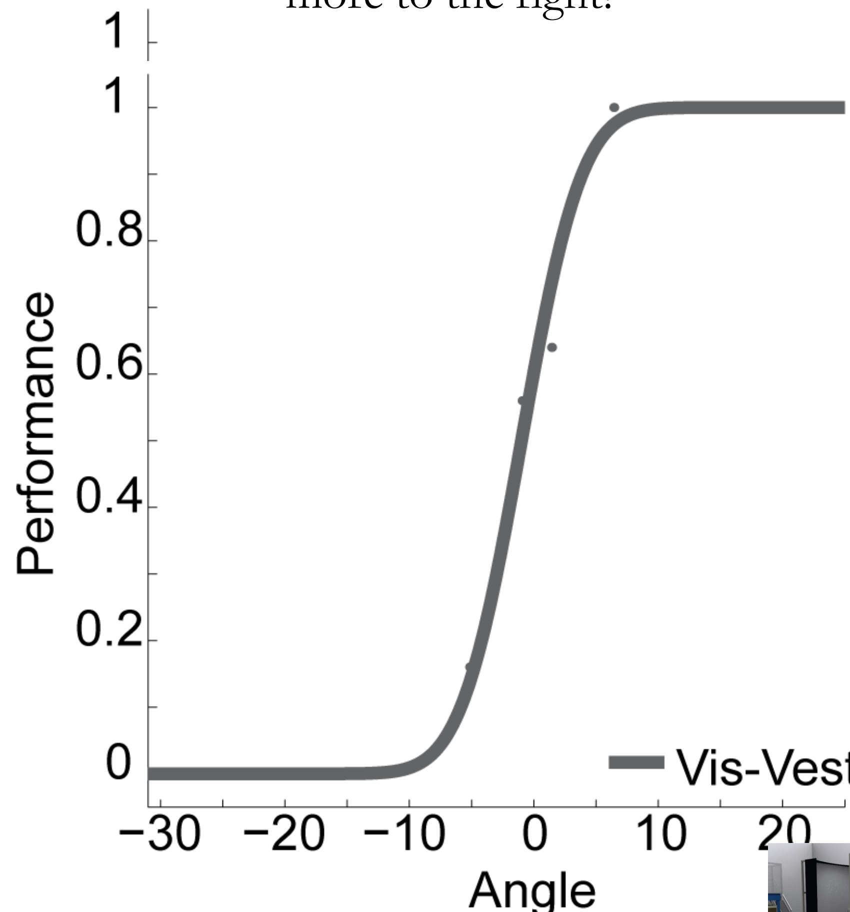


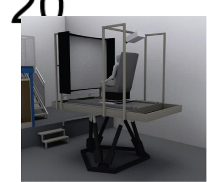


Reliability

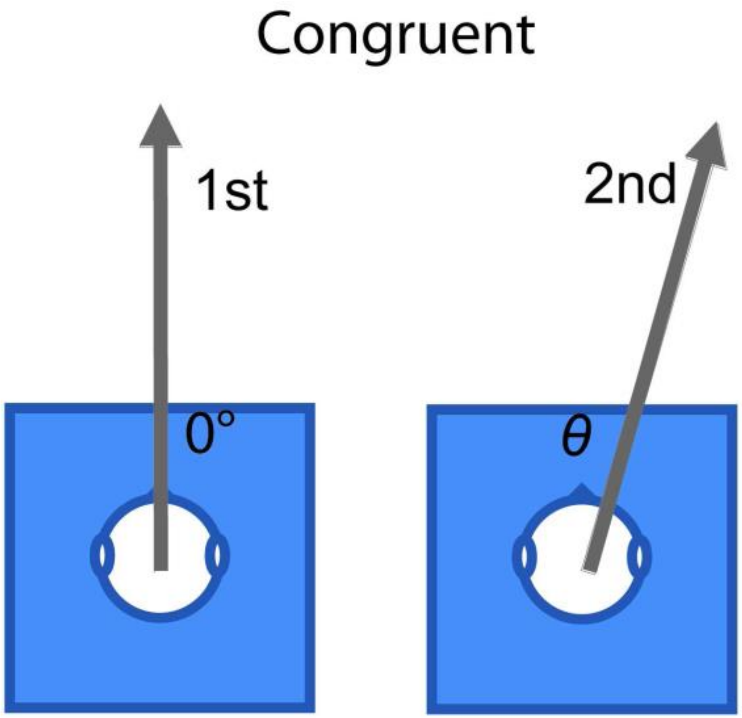


Was the second movement more to the right?



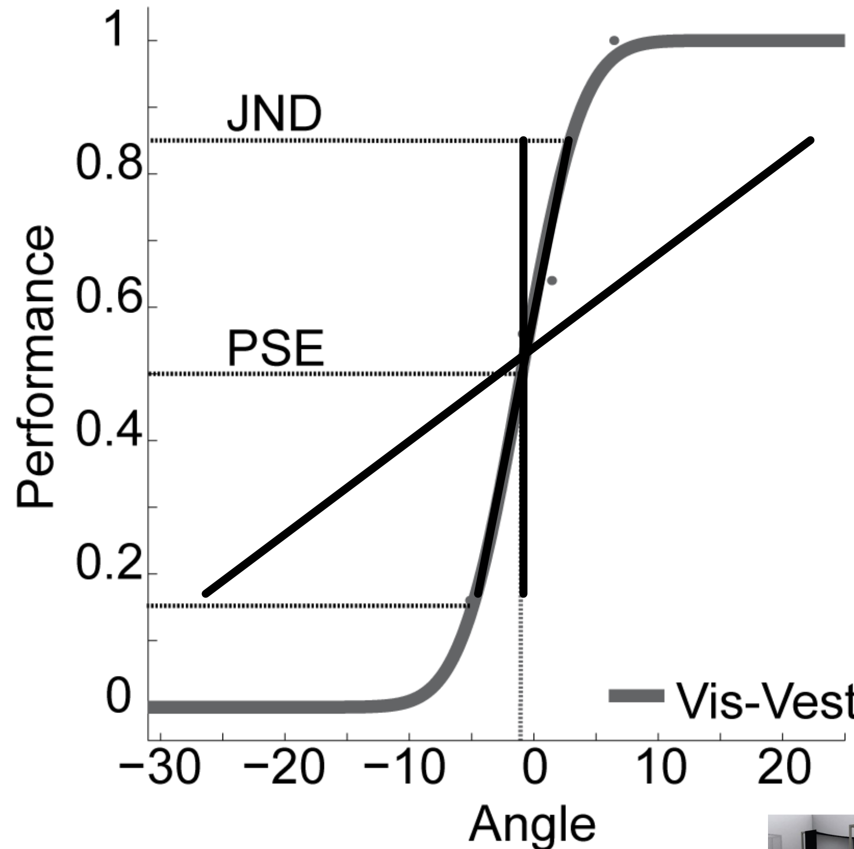


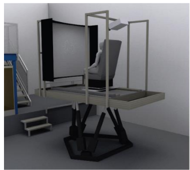
Reliability



Just Noticeable Difference (JND)

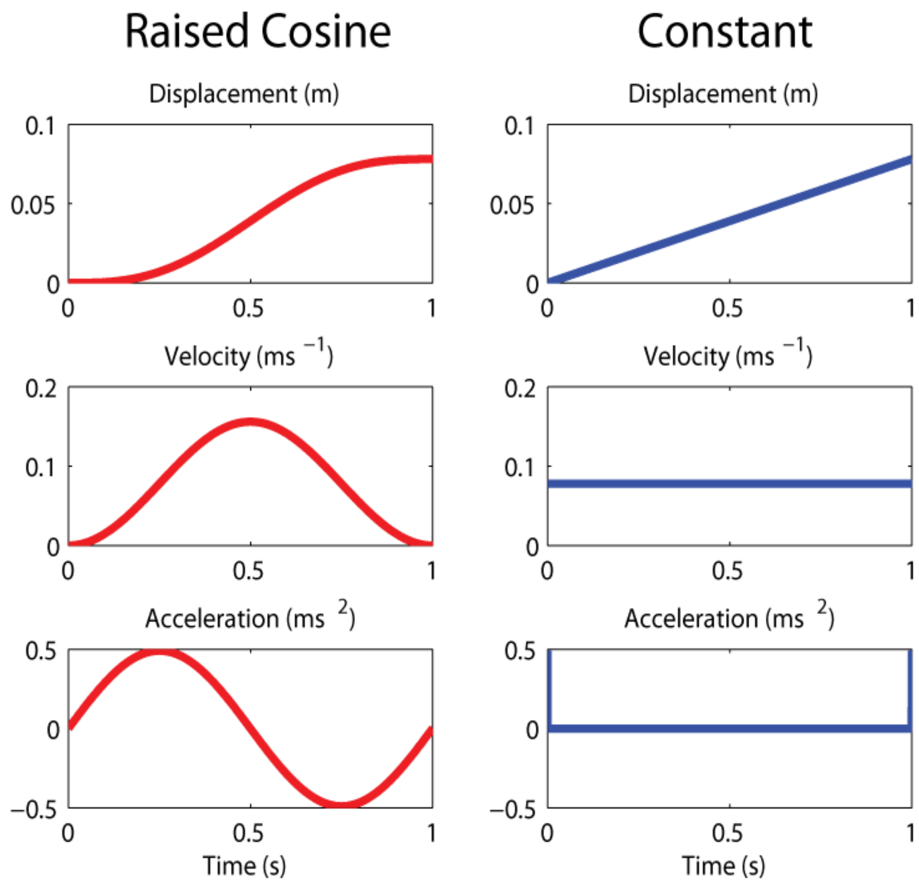
Was the second movement more to the right?

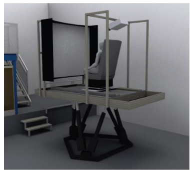




Information Conflict

- Conditions
  - Visual
    - Raised cosine
    - Constant velocity
  - Vestibular
    - Raised cosine
  - Visual-vestibular
    - Raised cosine velocity
    - Constant velocity (conflict)

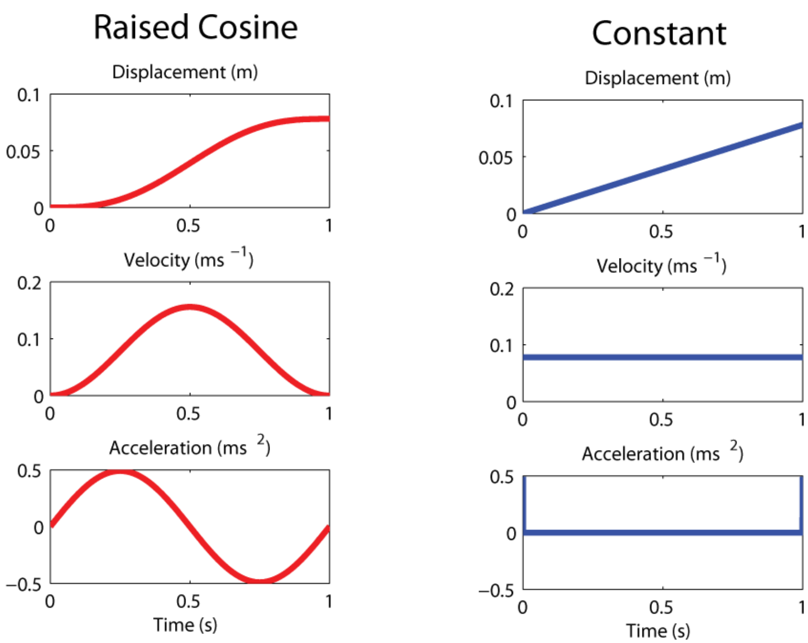




Visual motion Profile and heading estimation

Objective

To investigate if the velocity and acceleration play a role in visual heading discrimination



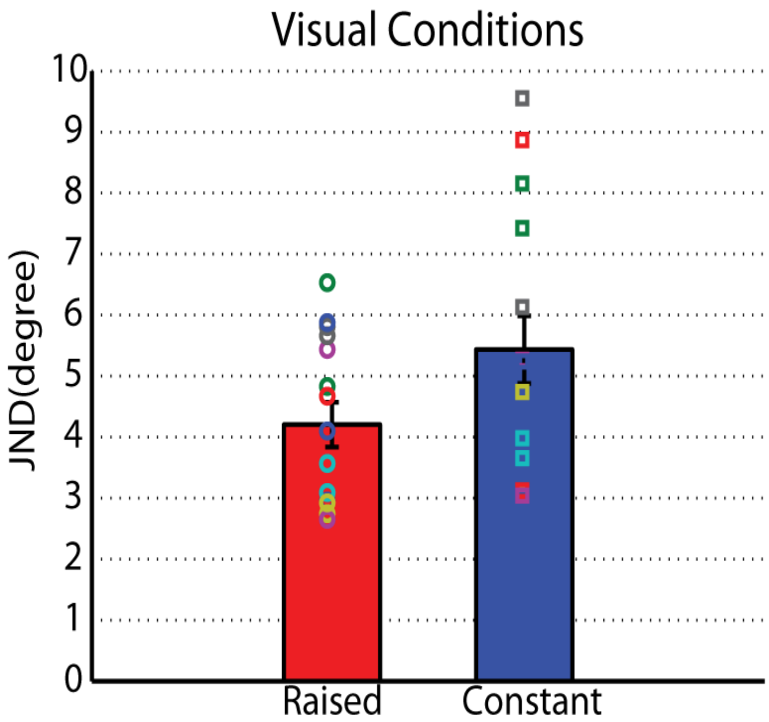
PREDICTION 1

The constant velocity profile will give more reliable results as it is highly predictable

PREDICTION 2

The more "natural" raised cosine profile is more reliably as we are more commonly exposed to it

Results

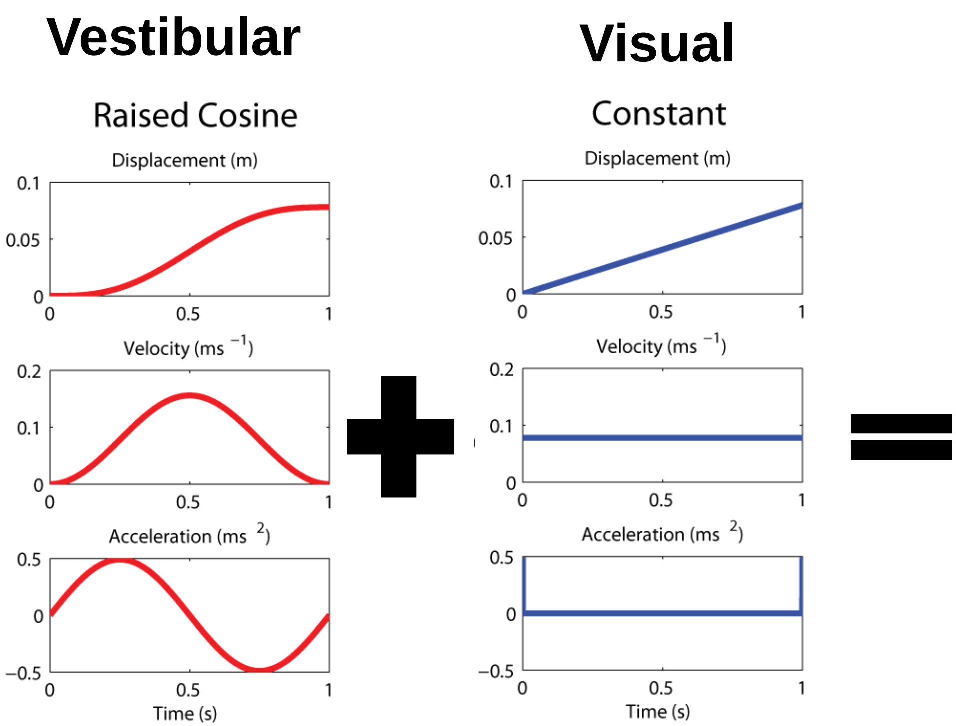


The raised cosine profile is gives more reliable estimates of visual heading

Predictions for the discrepant condition

Objective

To investigate the combination of visual and vestibular information under different visual motion profile conditions



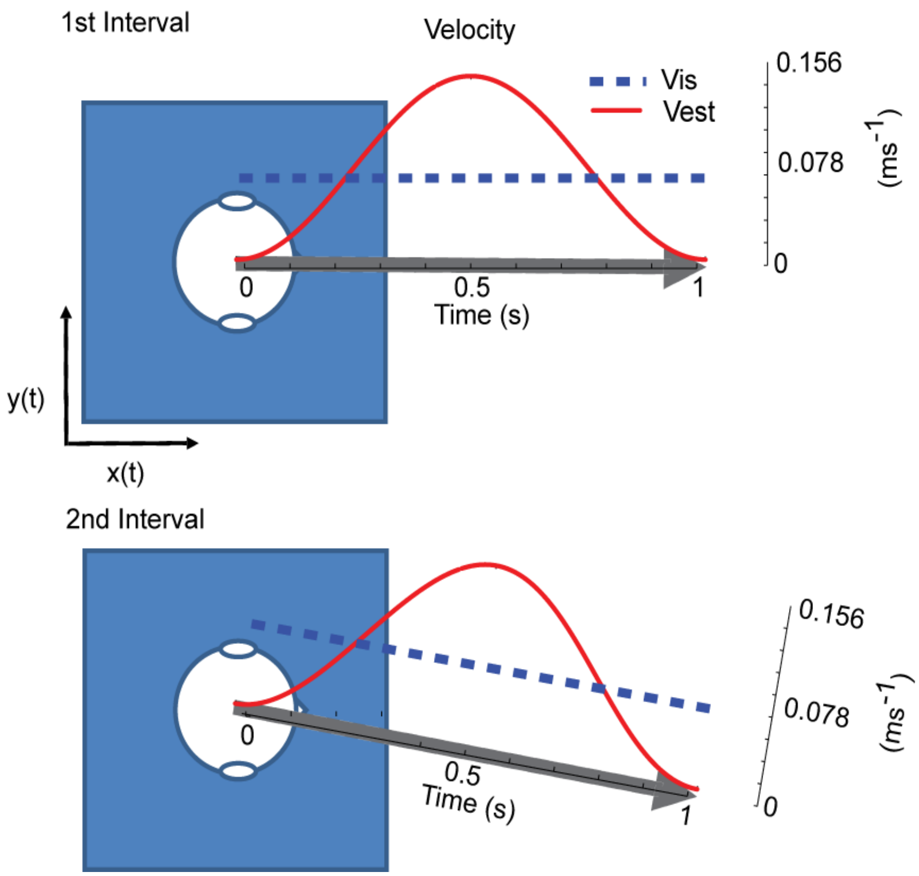
PREDICTION 1

The visual and vestibular information do not combine in an optimal fashion

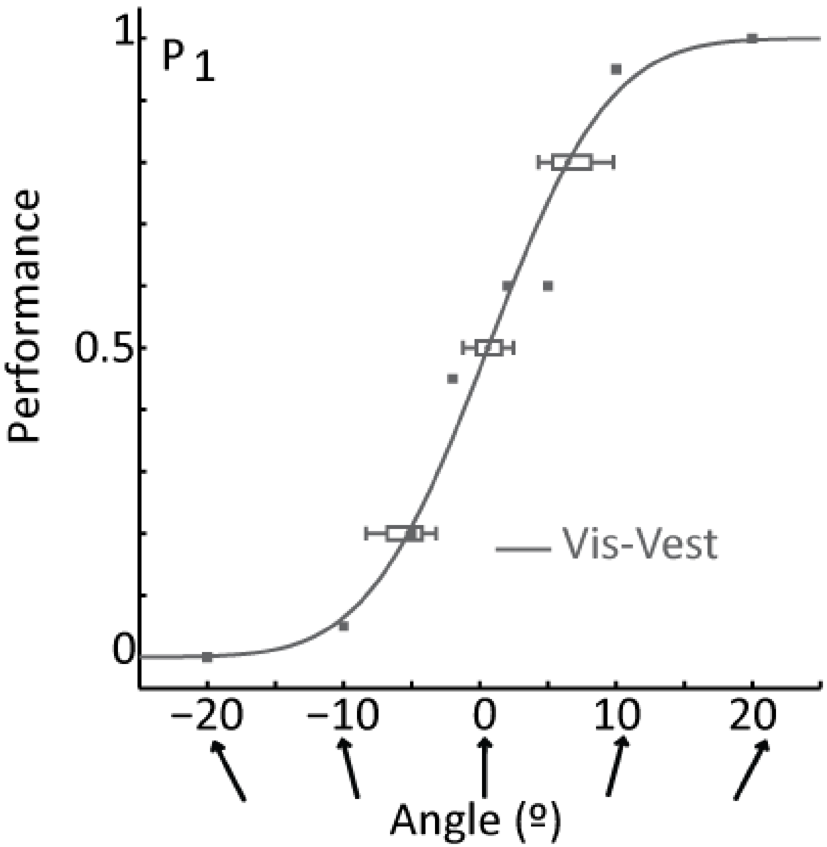
PREDICTION 2

Combination of senses is not dependent on the motion profile

Effect of visual motion profile on heading discrimination



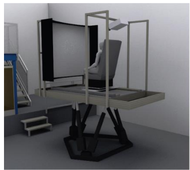
Combination of Senses



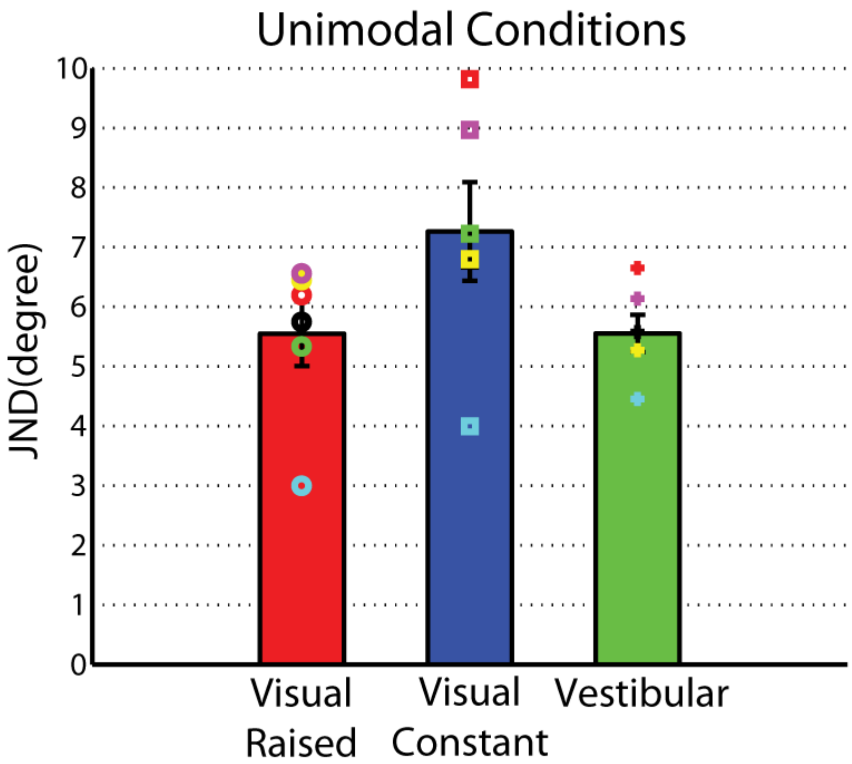
Predicted

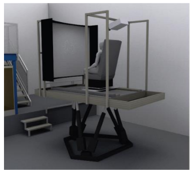
$$JND_{Vis-Vest} \leq \min(JND_{Vis}, JND_{Vest})$$

$$JND_{Vis-Vest} = \sqrt{\frac{JND_{Vis}^2 \, JND_{Vest}^2}{JND_{Vis}^2 + JND_{Vest}^2}}$$

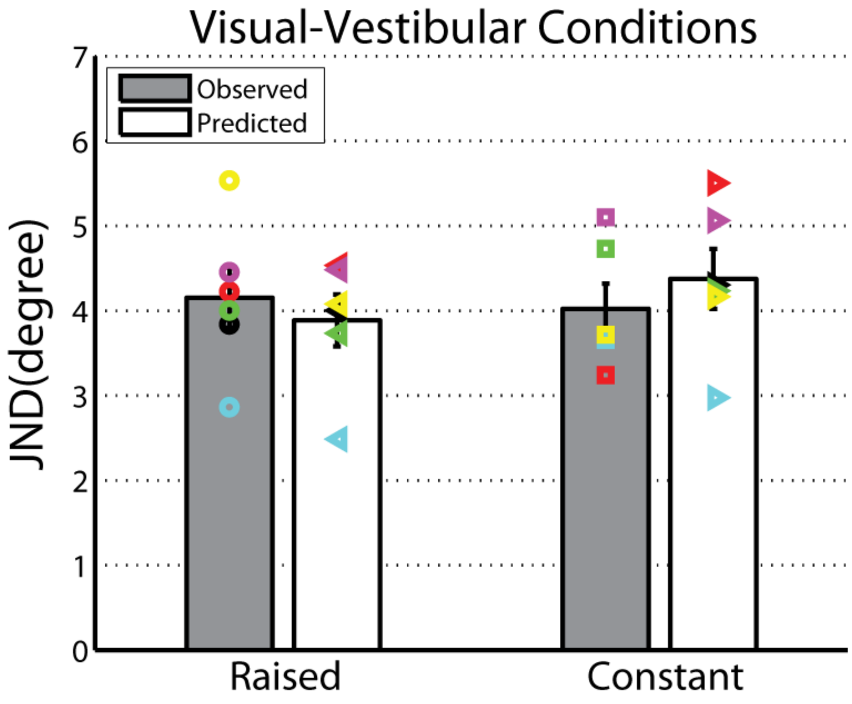


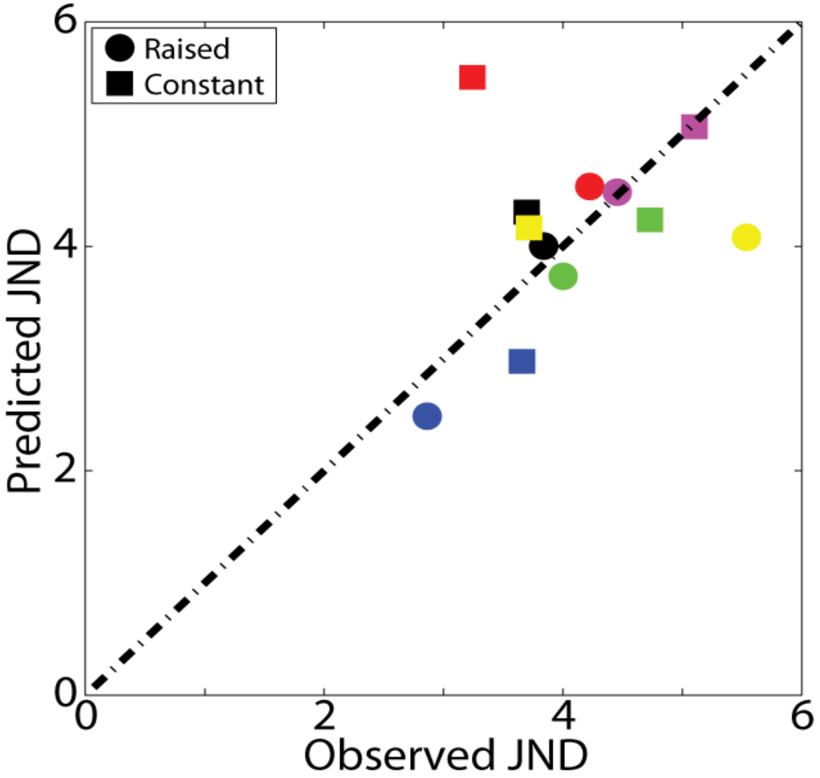
Unimodal results

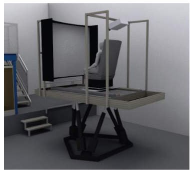




Multisensory Results







Conclusion

- Visual motion is not just a snap shot but an accumulation of information
  - The more natural profile yielded the more accurate heading discrimination
- Visual and Vestibular cues combine in an optimal fashion even when there is an information conflict

Visual-Vestibular Integration for Heading