Vestibular Perception: Rationale & Potential Applications

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October 10, 2024

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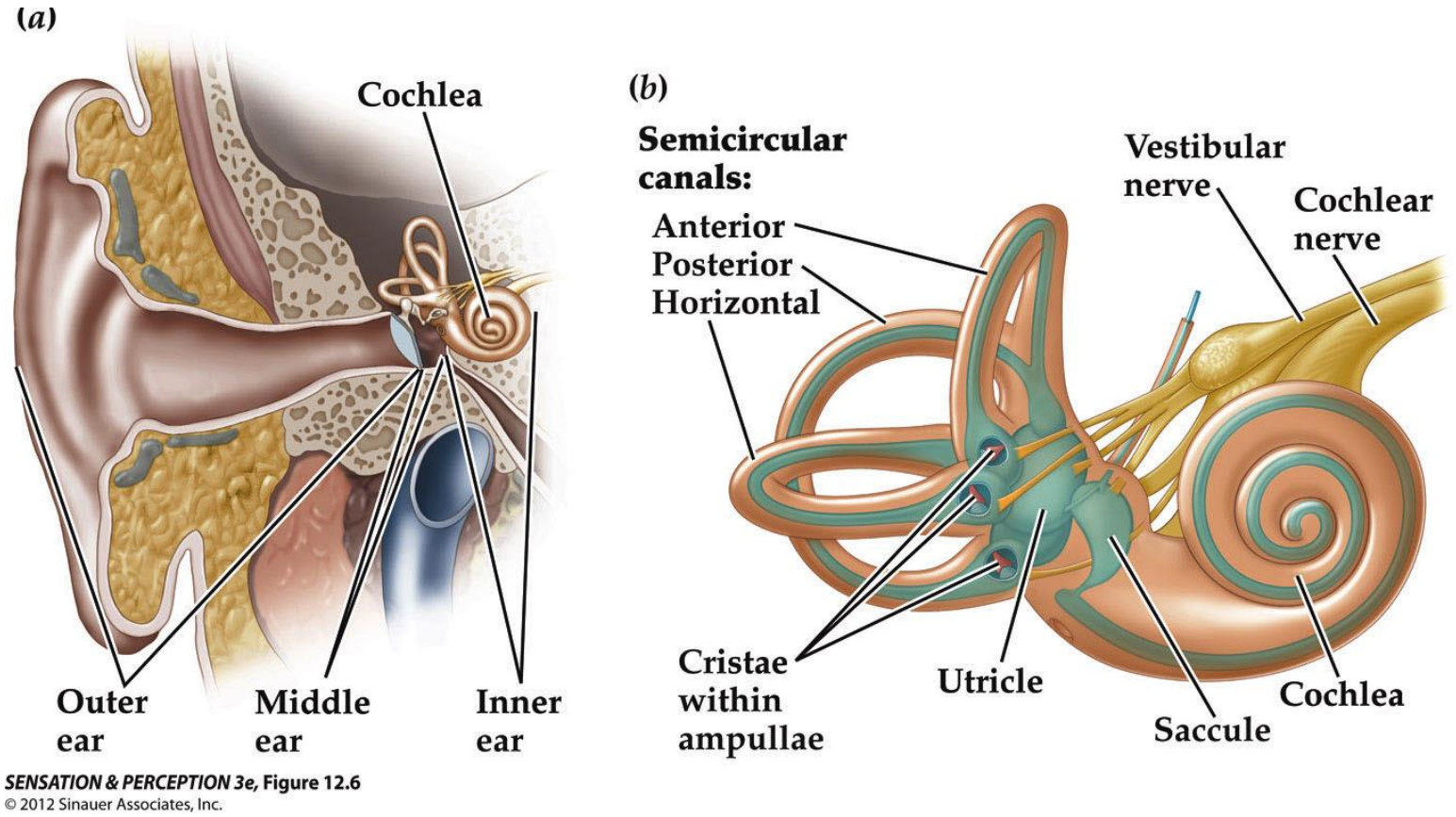
Disclosures

Megan Kobel AuD, PhD, has the following relevant financial relationships; she receives a salary from the University of Arizona and grant support from the National Institutes of Health (NIDCD, K01-DC021147) and has no non-financial relationships to disclose.

Objectives

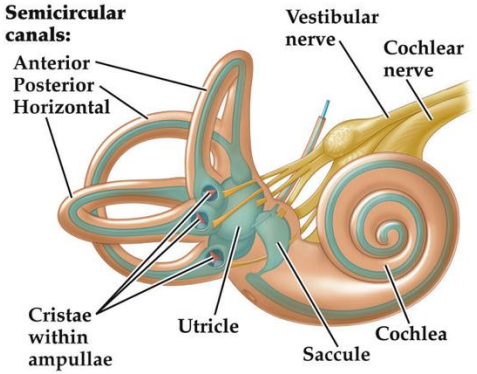
- Describe vestibular perceptual thresholds and the rationale underlying measurement techniques.
- Summarize how vestibular perceptual thresholds may change in peripheral and central vestibular disorders.
- Explain how accuracy and precision relate to measures of vestibular function.

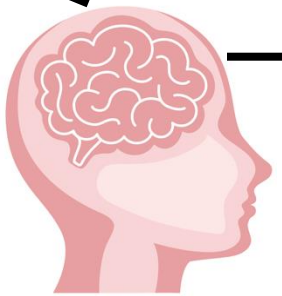
The peripheral vestibular system senses rotation, translation, and tilt



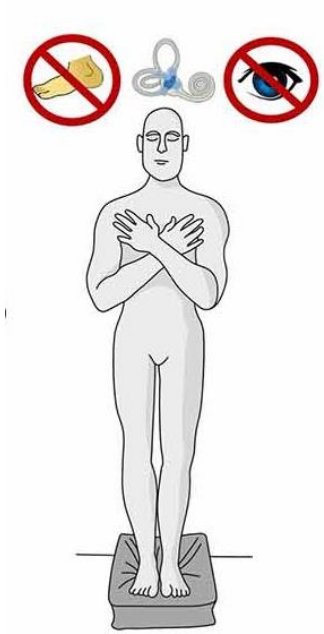
SENSATION & PERCEPTION 3e, Figure 12.6

The vestibular system contributes to many functions

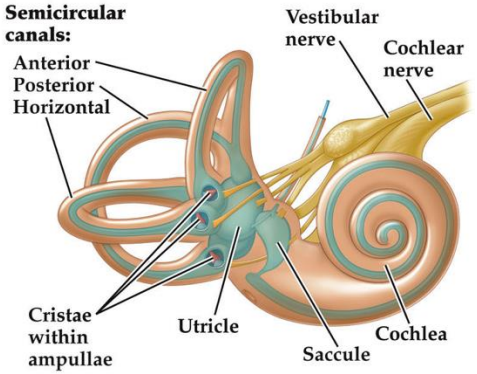


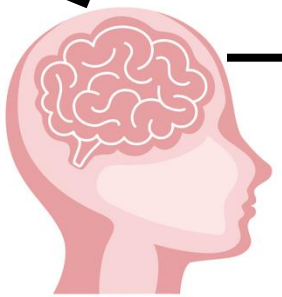


Posture & Balance



The vestibular system contributes to many functions



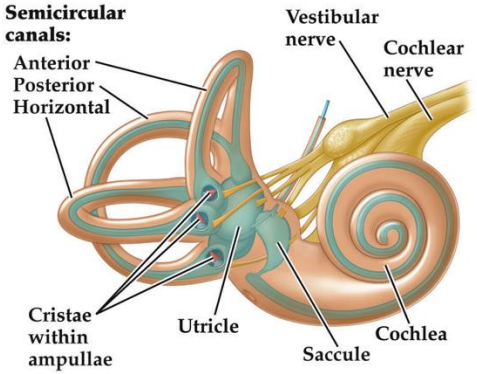


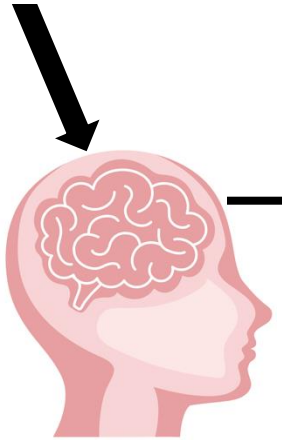
Balance

Visual stability

Vestibulo-ocular reflex (VOR)

The vestibular system contributes to many functions

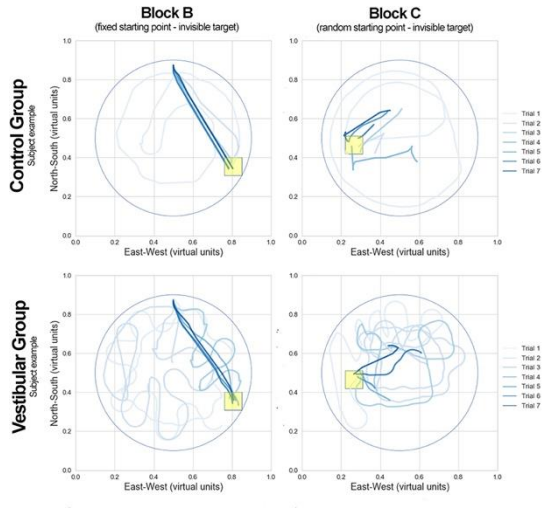




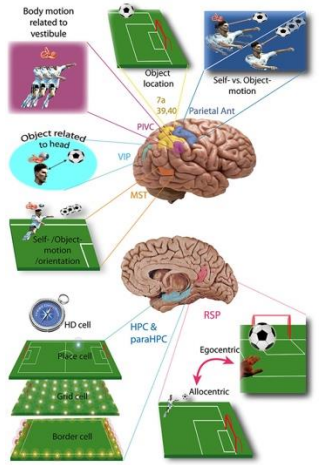
Balance

Visual stability

Spatial Orientation & Cognition

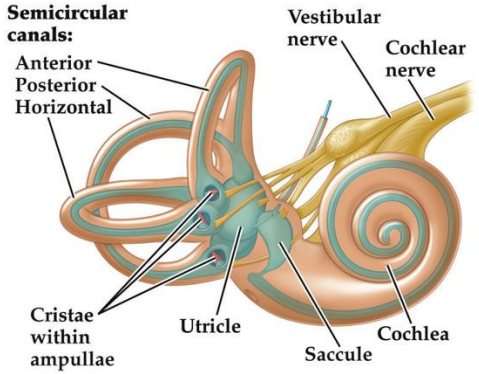


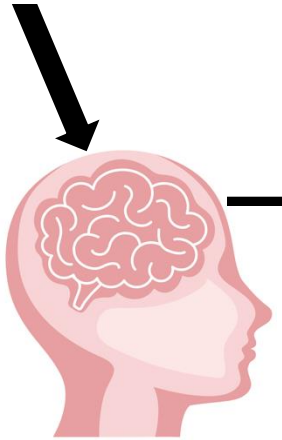
Breinbauer et al., 2020



Hitier al., 2020

The vestibular system contributes to many functions



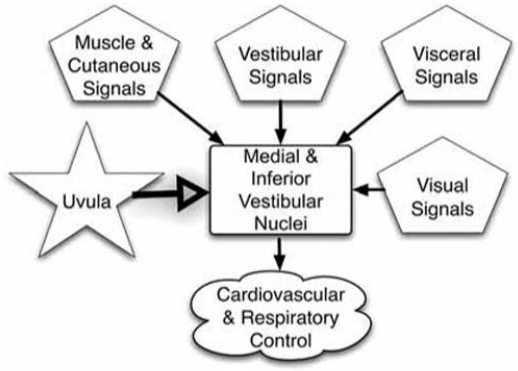


Balance

Visual stability

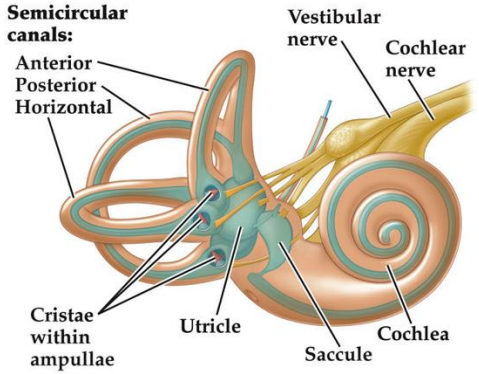
Spatial Orientation

Autonomic Responses



Yates et al., 2005

The vestibular system contributes to many functions

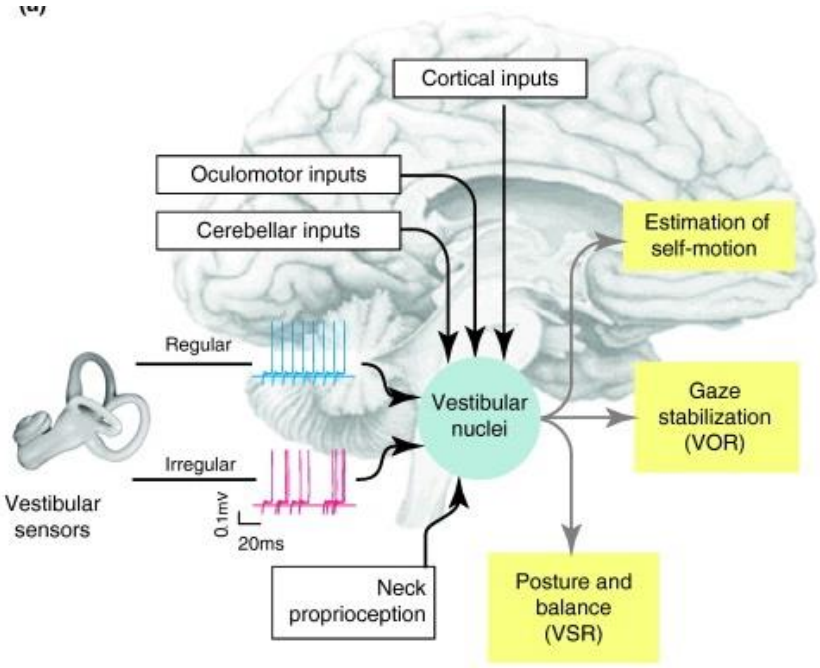


Balance

Visual stability

Spatial Orientation

Autonomic Responses

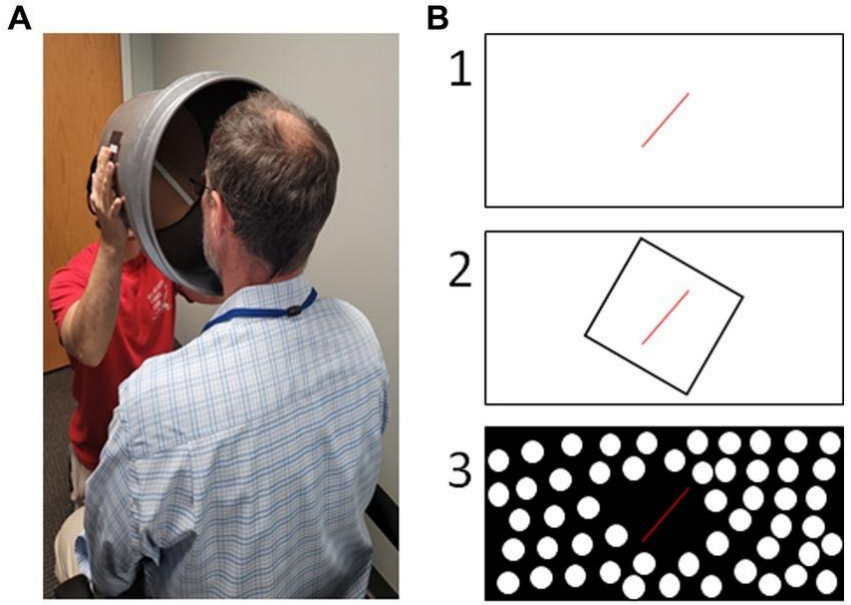


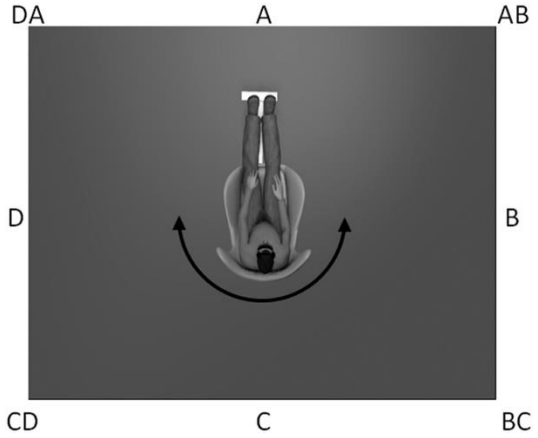
Why study vestibular perception?

- Almost 40% of Americans will seek medical care for symptoms of vestibular dysfunction (NIDCD, 2018).
- Measures of reflexes unrevealing in many patients (Phillips et al., 2009) and do not correlate to function or handicap (Gofrit et al., 2017).
- Vestibular perception gives insights into unique pathways (Cullen, 2009).
  - Vestibular symptoms defined in terms of sensation and perception (ICVD, 2017)

What constitutes vestibular perception?

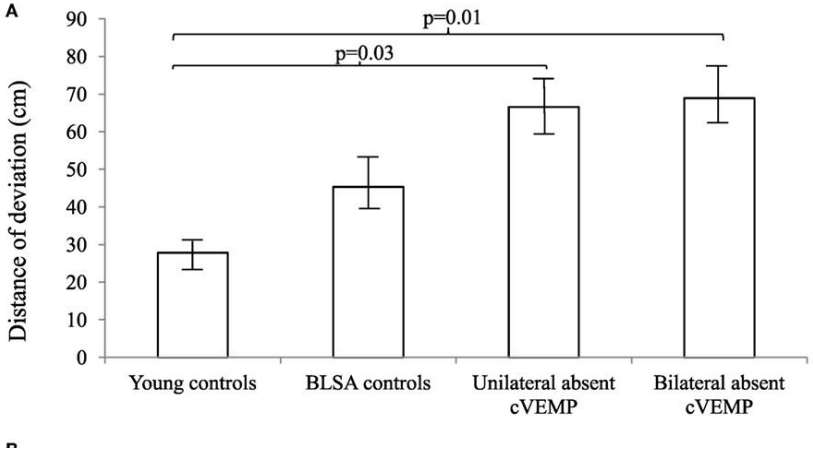
- **Verticality perception**
  - Dependent on integration of otolith & visual cues
  - Sensitive to vestibular & non-vestibular dysfunction (Deitrich et al., 2021)
- **Spatial orientation**
  - Dependent on integration of vision, vestibular, somatosensory cues, and allocentric spatial cues
  - Variable methodologies; test-retest and normative values not established

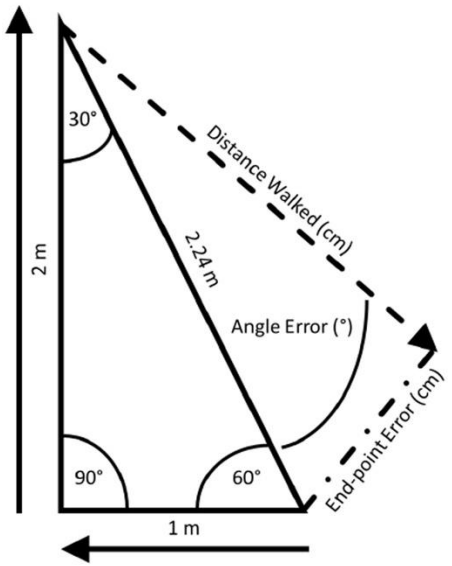




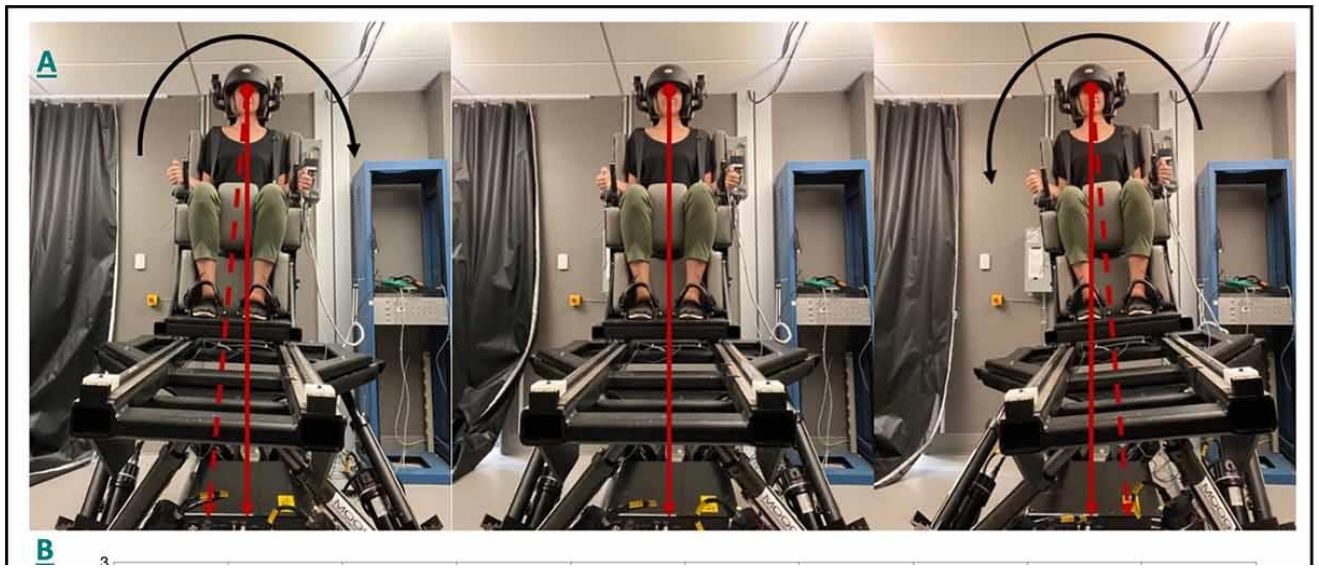
What constitutes vestibular perception?

- **Spatial Navigation**
  - Complex sensorimotor skill which is impacted by peripheral, central, and age-related vestibular dysfunction
  - Vestibular deafferentation can impact path integration (Glassauer et al., Cohen et al.,)
- **Vestibular Cognition**
  - Evidence to suggest patients with UVH, BVH, VM, and MD display changes in spatial and non-spatial cognition (Chari et al., 2022, Li et al., 2024)





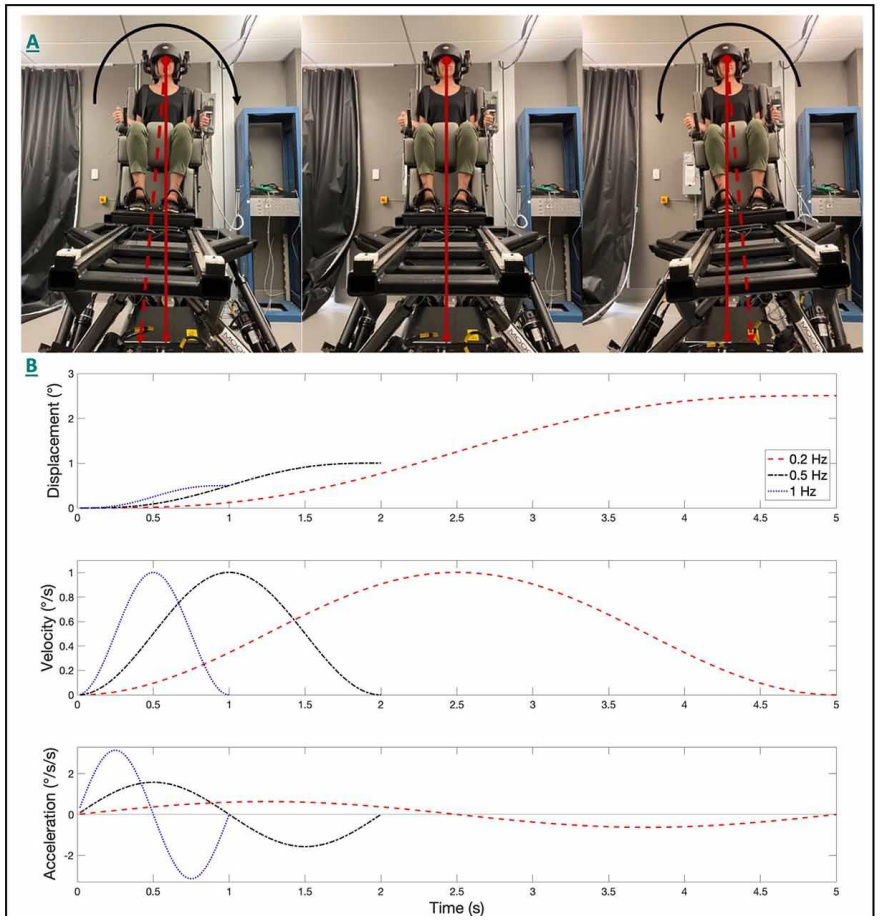
Vestibular Perception: Vestibular Thresholds



- Quantify individual's sensitivity to passive self-motion cues
- Tasks have predominant vestibular contributions (Grabherr et al, 2008; Kobel et al., 2023, 2024)

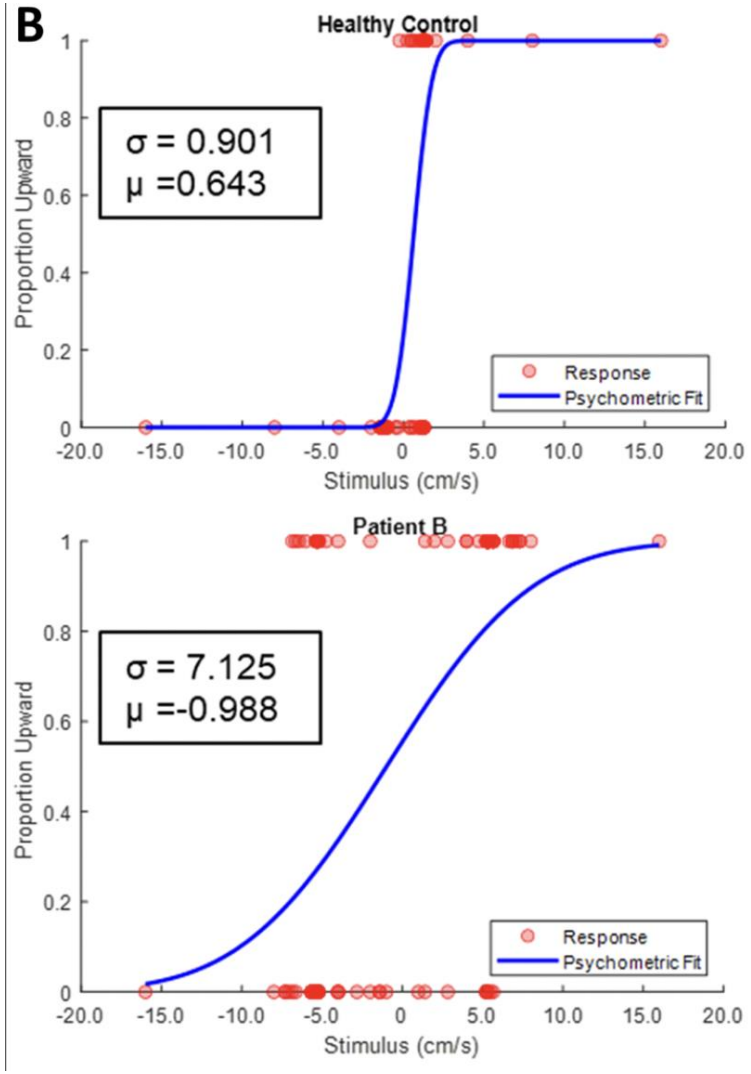
Vestibular Perception: Vestibular Thresholds

- Direction recognition task is the most commonly used methodology
  - Two to twelve interval has been used (Dupuits et al., 2019; van Spithout et al., 2021)
  - Adaptive staircases typically used for stimulus magnitude selection
  - Stimuli are single cycles of sinusoidal acceleration
- Other methodologies can be employed (e.g., Cousins et al., 2017)



Psychophysics & Perception

- Fitting of psychometric curve allows all trials to be included
- Two parameters extracted from psychometric curve:
  - μ = bias = offset from zero
  - σ = sigma = width of psychometric function
- Typically, one-sigma thresholds are reported



Vestibular Perception: Test Batteries

Vestibular end-organ	Motion(s)	References
Lateral canals	Earth vertical yaw rotations	(51, 62, 63)
Vertical canals	Earth horizontal tilts (≥2 Hz*) earth vertical rotations	(56, 62–64)
Utricles	Interaural translations (<2 Hz**) quasi-static tilts	(24, 53, 62–64)
Saccules	Superior–inferior translations (<2 Hz**) quasi-static tilts	(53, 62, 63)
Canal-otolith integration	Earth horizontal tilts (<1 Hz***)	(56, 62–64)

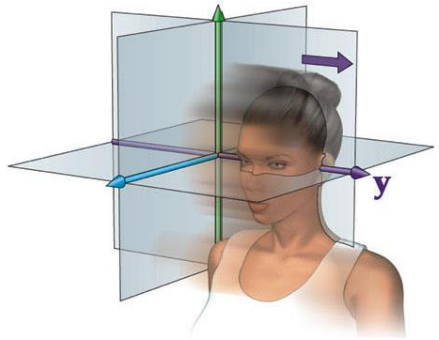
Grove et al., 2023

- Can “isolate” specific vestibular end-organ contributions to motion perception based on plane & frequency

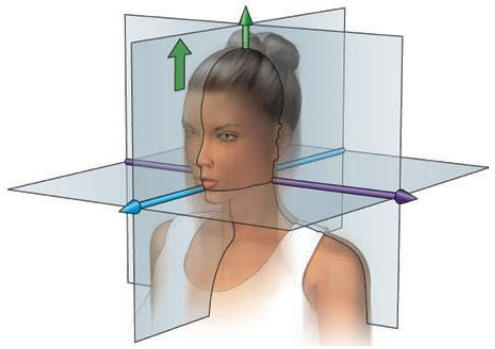
Vestibular Perception: Planes of Motion

Translations

Utricle

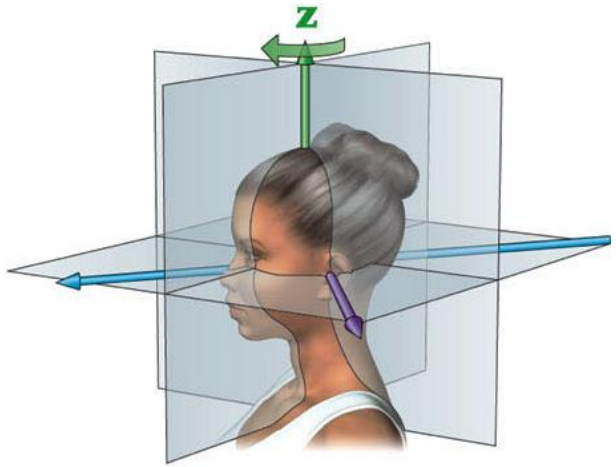


Saccule



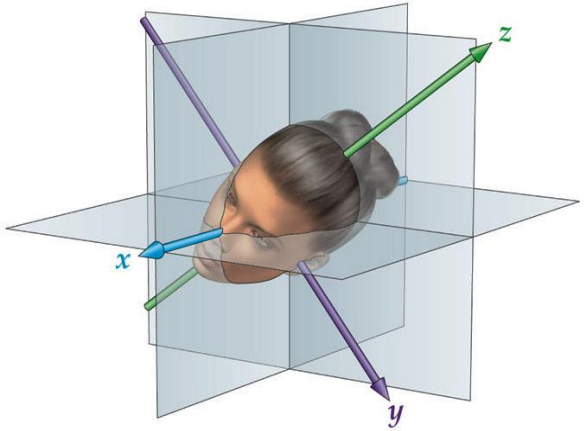
Rotations

Horizontal Canal

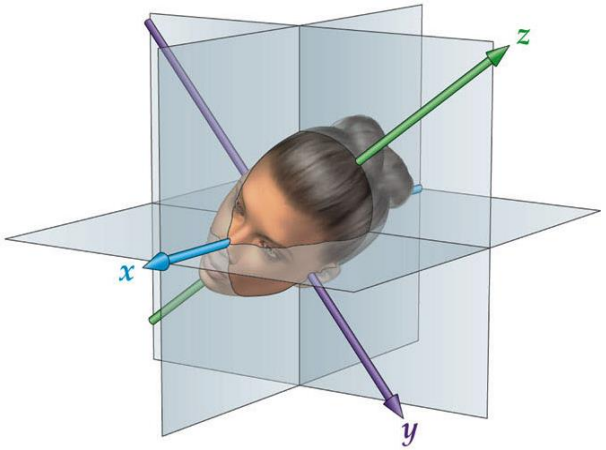


Tilts

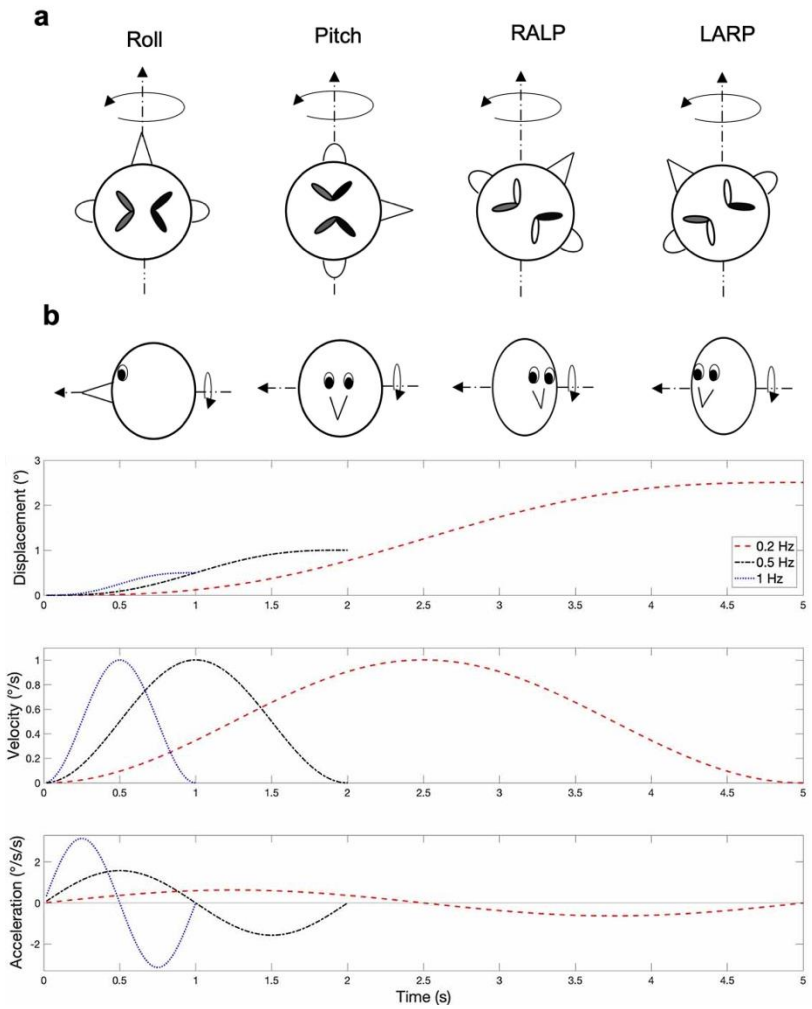
Canal + Otolith

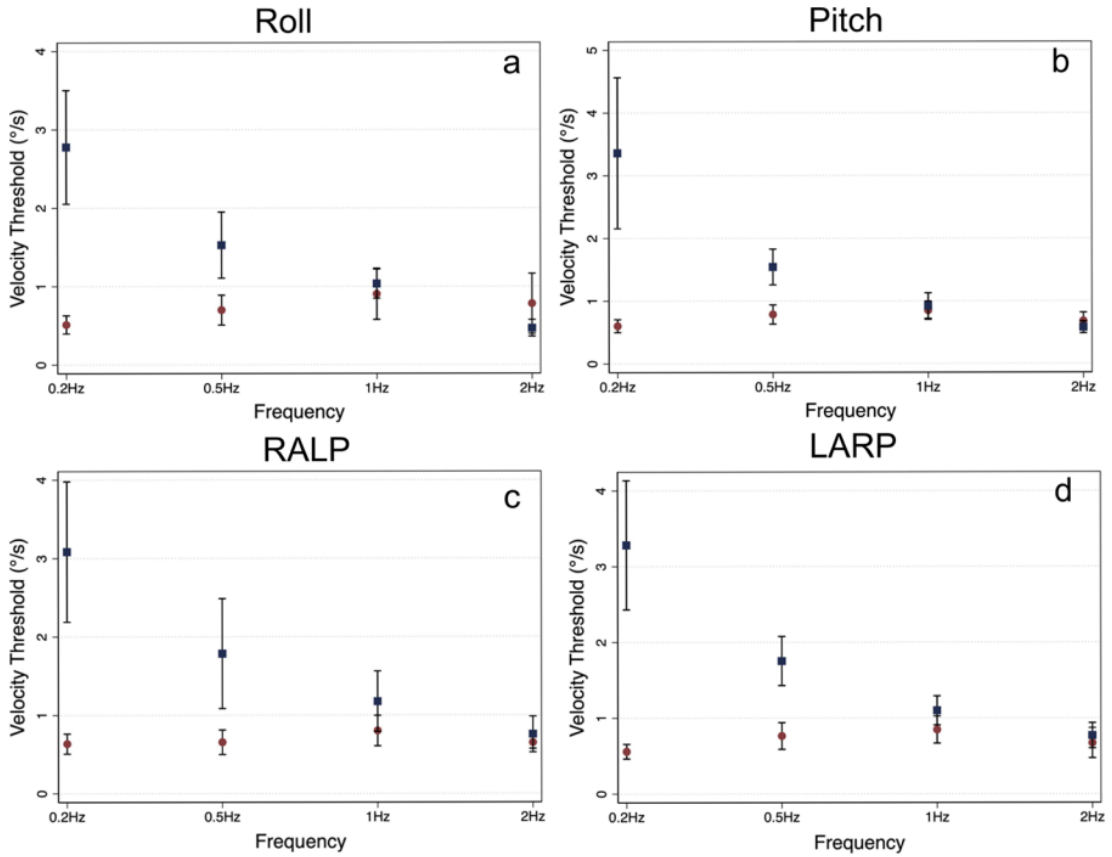


Canal



Vestibular Perception: Frequency





Wagner et al., 2022

Vestibular Perception: Frequency

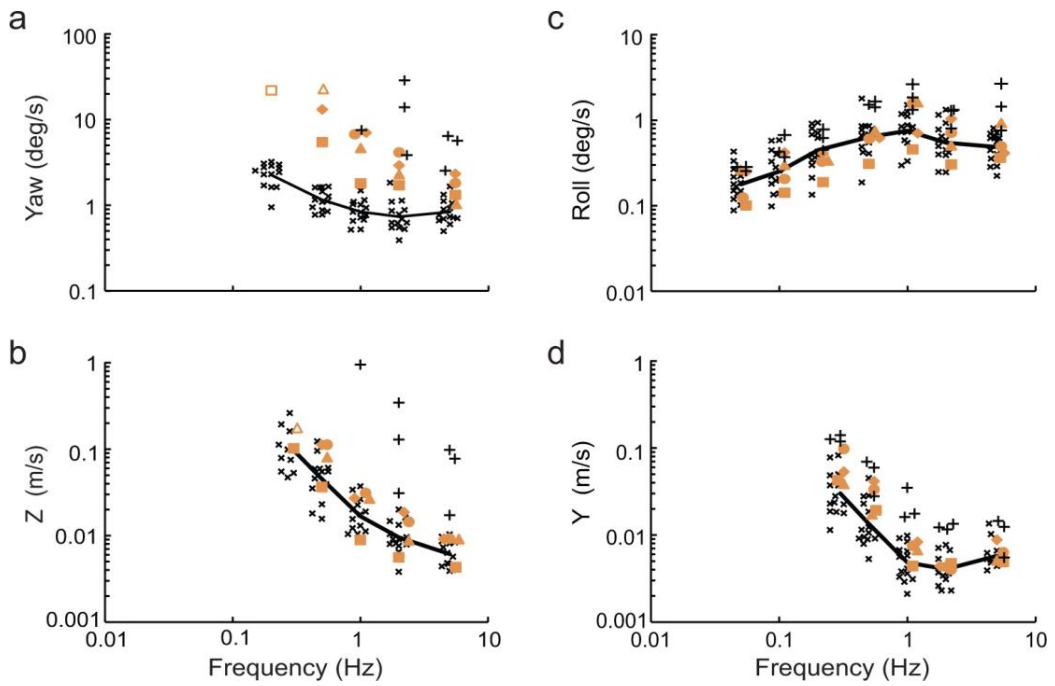


Table 3. Normalized average thresholds for 3 total bilateral loss patients

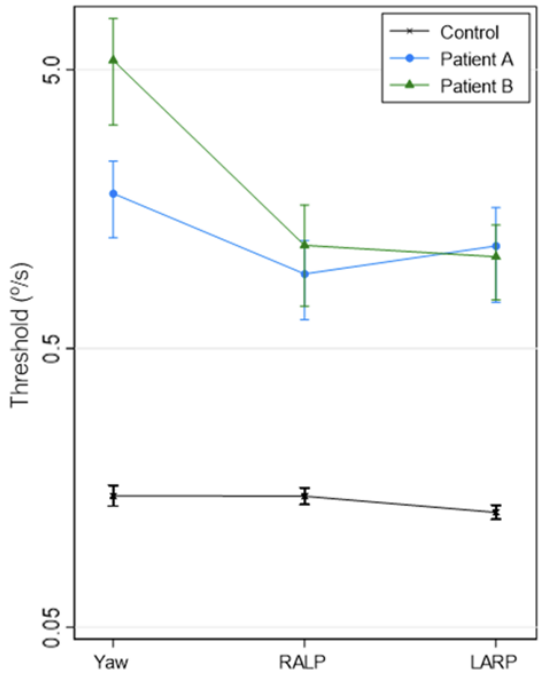
Frequency (Hz)	Yaw	Roll	*z*	*y*
0.05		1.53		
0.1		1.88		
0.2		1.34		
0.3				4.25
0.5		2.4		3.61
1	9.01*	2.47	56.78*	4.45
2	15.69	2.03	11.69	3.06
5	5.4	2.95	8.28	1.73

Data are normalized by the average of the normative data (defining the normal average to equal "one"). Asterisks (*) show two conditions that include only one patient; thresholds for other two patients could not be assayed for these two conditions because requisite motion exceeded device limits.

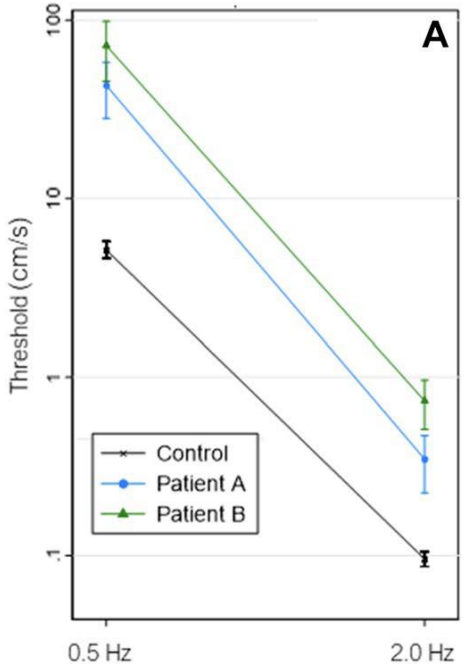
- In bilateral vestibular ablation, thresholds at lower frequencies elevated more suggesting increased vestibular contributions

Vestibular Perception: Bilateral Vestibular Loss

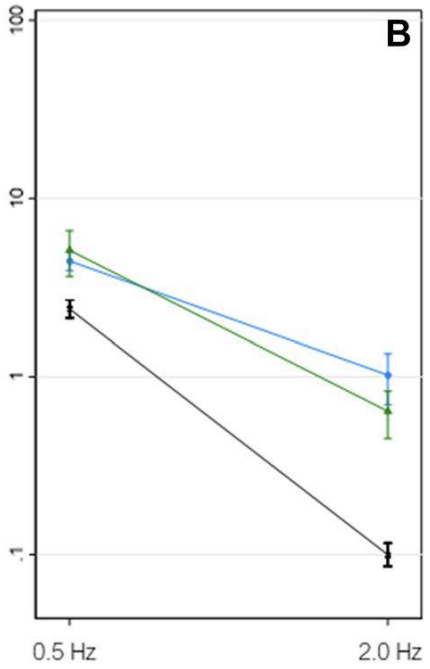
Yaw Rotation



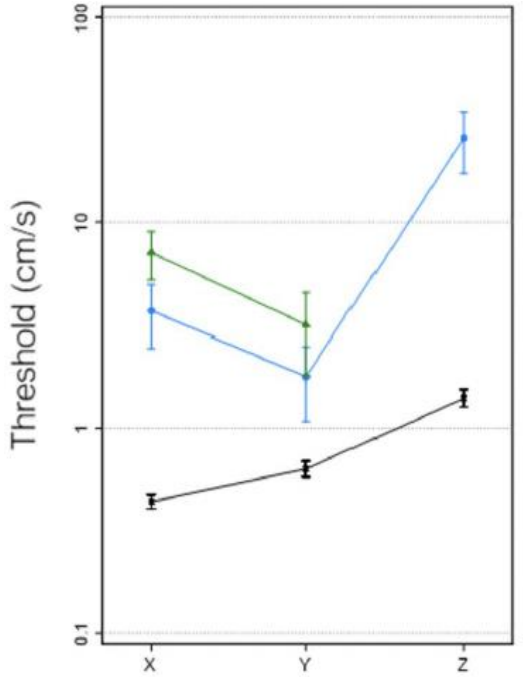
Supine Roll



Roll tilt



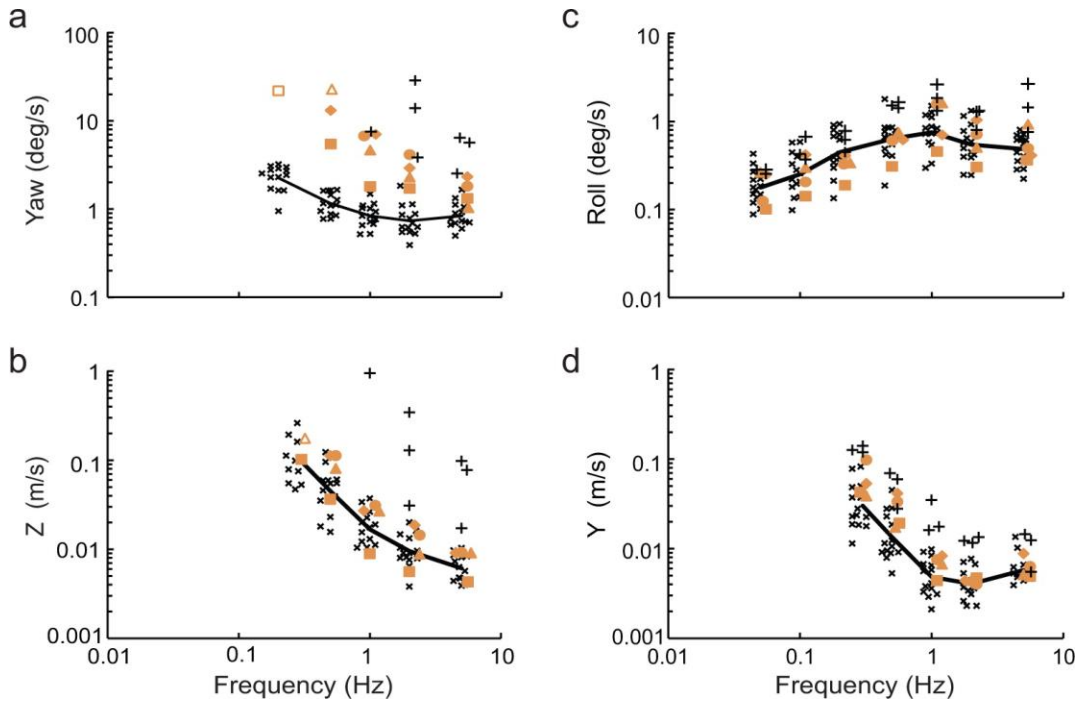
Translation



Kobel et al., 2023; 2024

- Thresholds elevated by ~1.5-84x in complete bilateral ablation (Valko et al., 2012; Kobel et al., 2023, 2024)
- How thresholds impacted by lesser degrees of vestibular pathology is less well categorized

Vestibular Perception: Peripheral Loss



- Some evidence to suggest can localize impacted vestibular structures
- Priesol et al. (2014) found patients with horizontal SCC pathology had isolated higher yaw thresholds

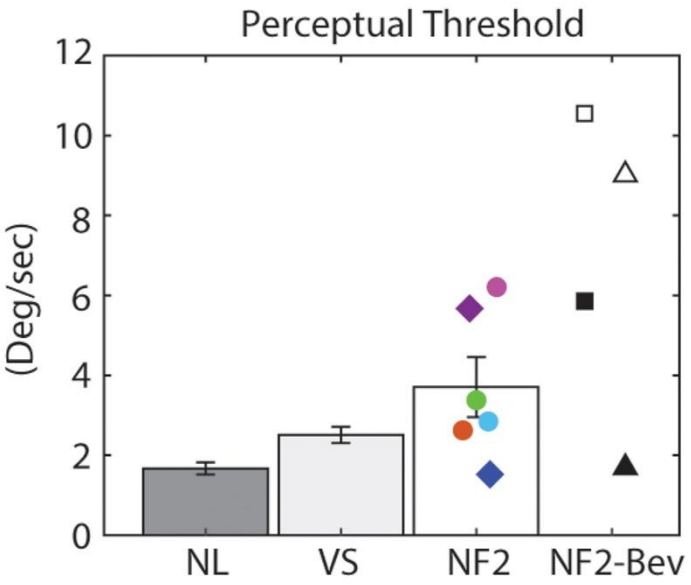
Vestibular Perception: Peripheral Loss

TABLE 2

Mean (SD) linear motion perceptual thresholds by normal and abnormal VEMPs in age-adjusted ANCOVA analyses in total study group (*N*=75)

		oVEMP				*cVEMP*			
Perceptual threshold		*Normal*[a] *(mean (SD))*	*Abnormal*[a] *(mean (SD))*	*F statistic*[b]	*p value*[c]	*Normal*[a] *(mean (SD))*	*Abnormal*[a] *(mean (SD))*	*F statistic*[b]	*p value*[c]
Sigma IA	**Y**	*11.3 (7.9)*	*19.4 (6.9)*	*7.15*	*0.0093*	10.8 (8.1)	19.1 (6.4)	3.27	0.0758
Sigma NO	**X**	*11.1 (8.5)*	*19.7 (6.6)*	*5.00*	*0.0285*	10.7 (8.6)	19.9 (6.2)	1.73	0.1938
Sigma HV	**Z**	17.8 (6.8)	22.4 (3.4)	1.67	0.2000	17.4 (7.0)	22.5 (3.8)	0.57	0.4542

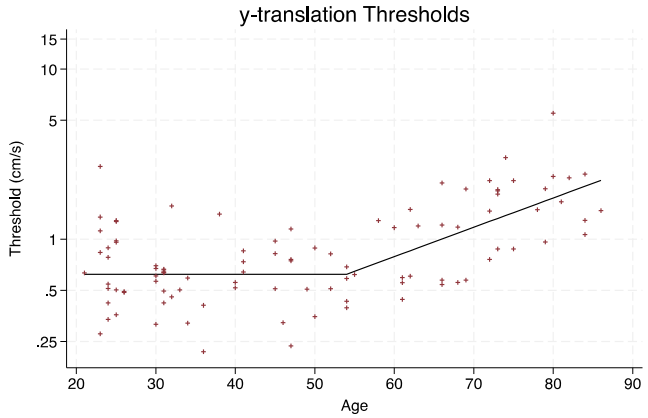
- Agrawal et al. (2013) found that oVEMP abnormalities associated with horizontal plane translations
  - cVEMP abnormalities did not correlate to translation thresholds

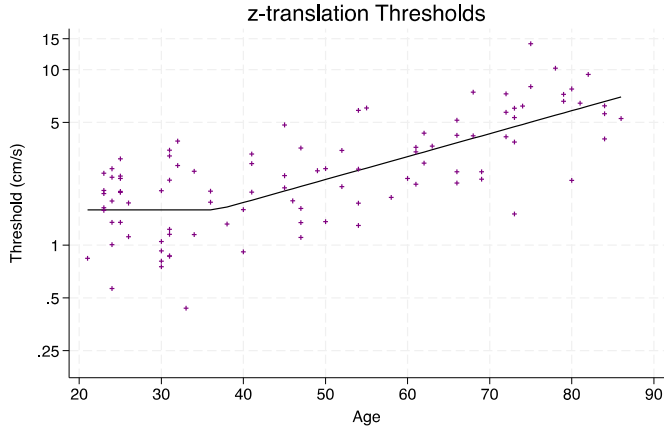


- Madhani et al. (2022) found elevated thresholds in patients with NF-2 (*N* = 5 bilateral and *N* = 3 unilateral) and 38 participants with sporadic unilateral vestibular schwannomas

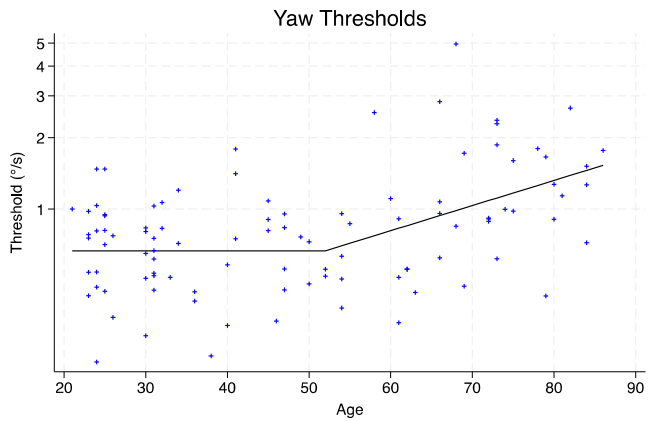
Vestibular Perception & Aging

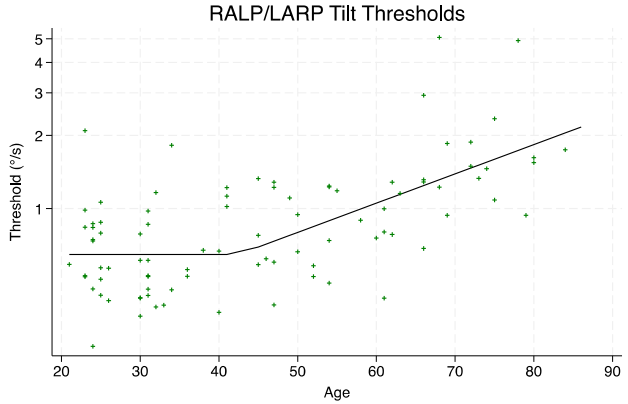
Otolith Function



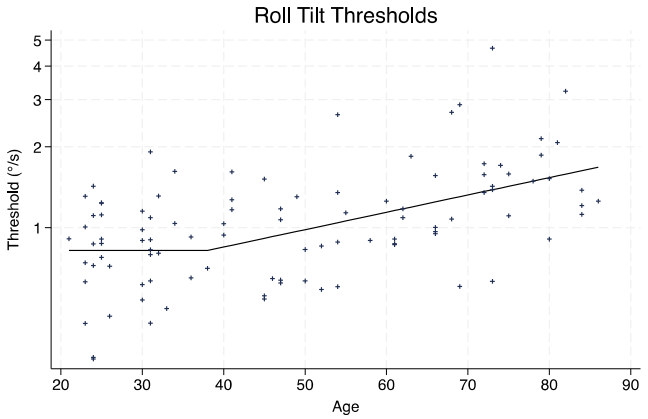


Canal Function



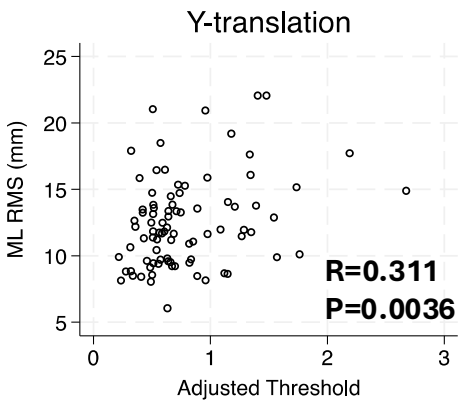


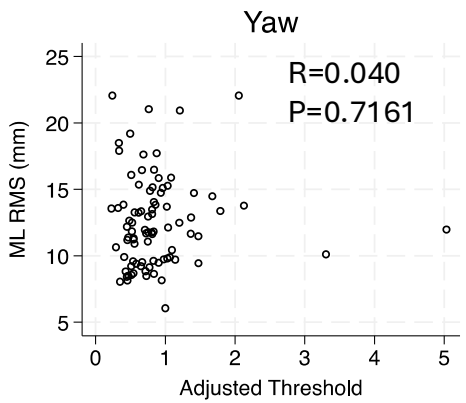
Canal + Otolith Function

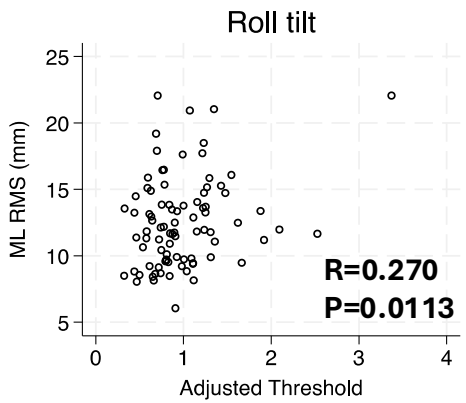


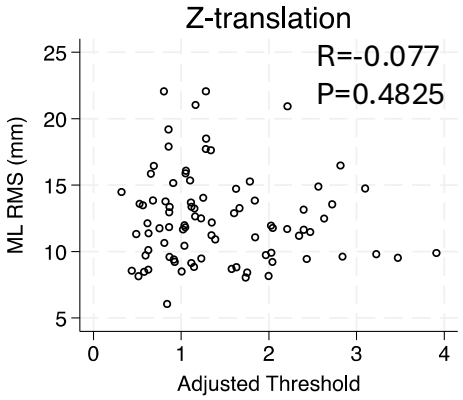
Threshold	Structure	Age Cutoff
Yaw rotation	Horizontal SCC	52.00
RALP tilt	Vertical SCC	42.49
Roll tilt	Canal + Otolith	38.01
y-translation	Utricle	54.00
z-translation	Saccule	36.81

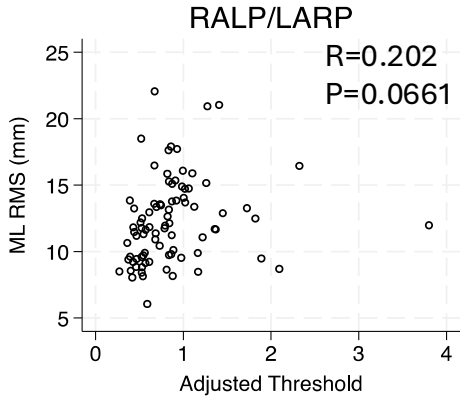
Vestibular Perception & Balance



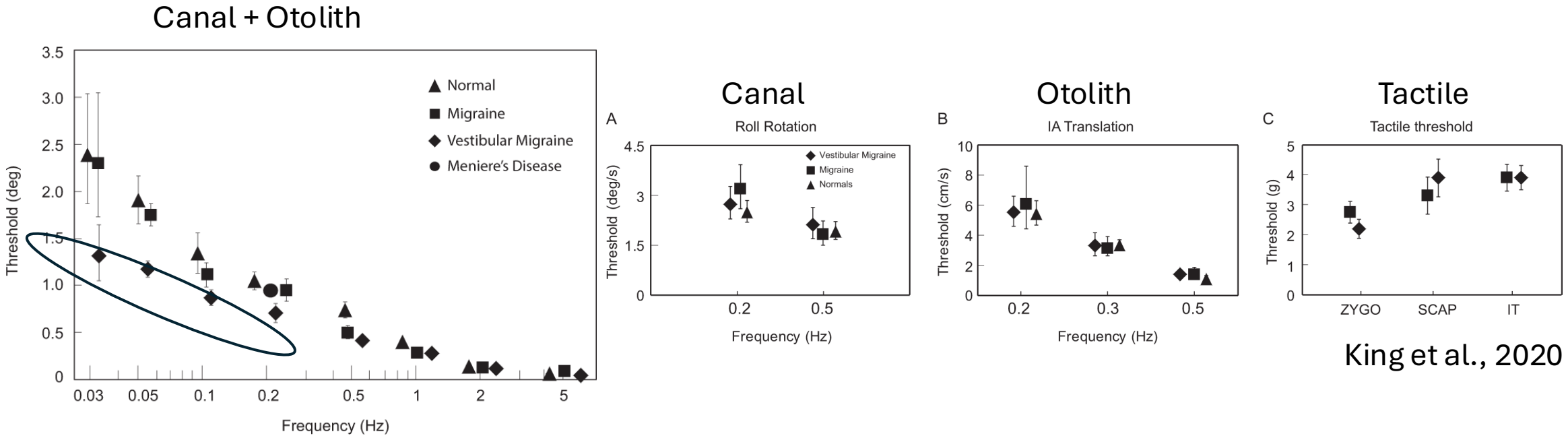








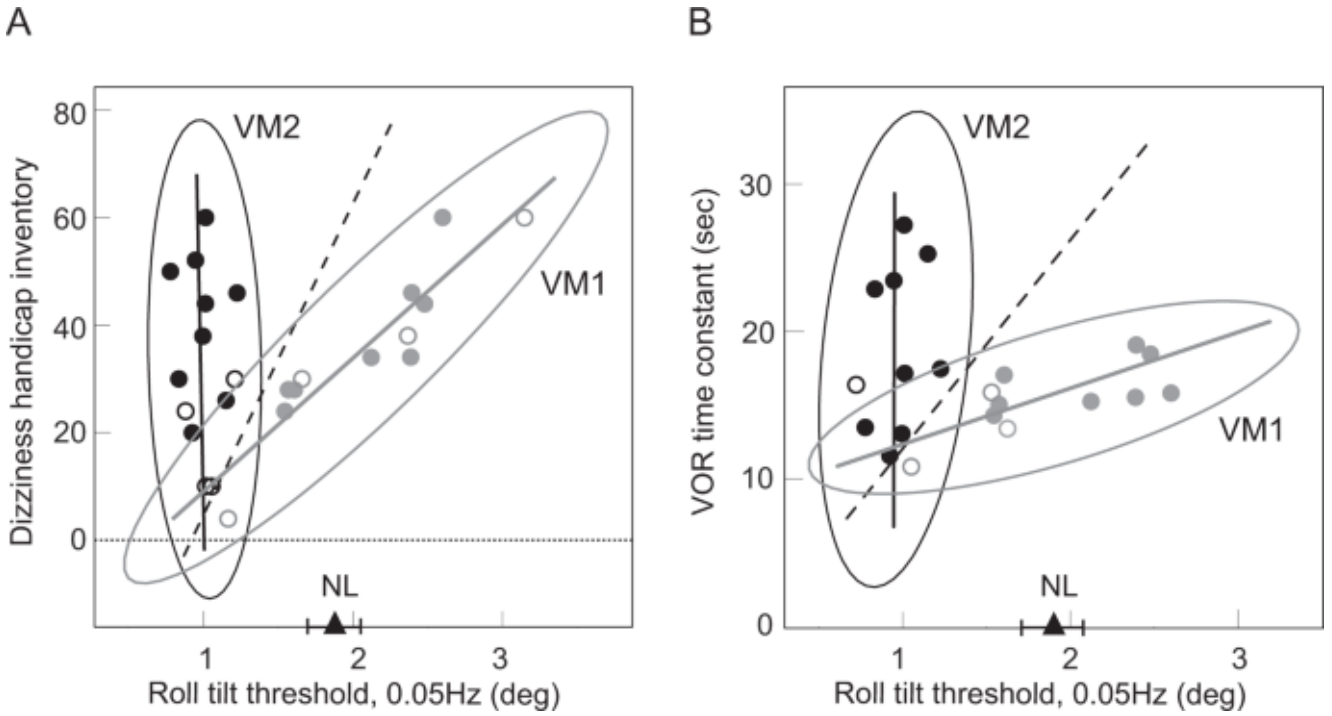
Perception: Vestibular Migraine



King et al., 2020

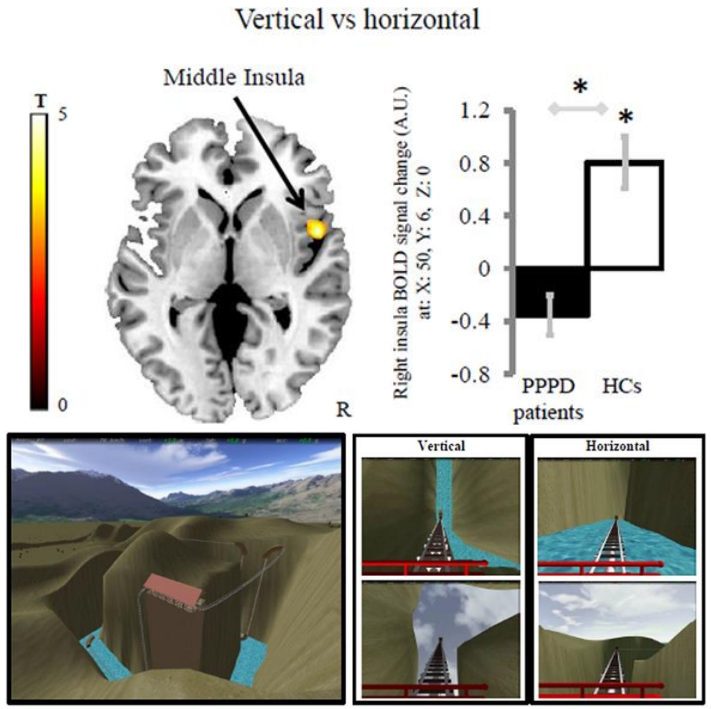
- Patients with vestibular migraine show decreased thresholds for motion reliant on canal-otolith integration (Lewis et al, 2011a,b; King et al., 2020)

Perception: Vestibular Migraine

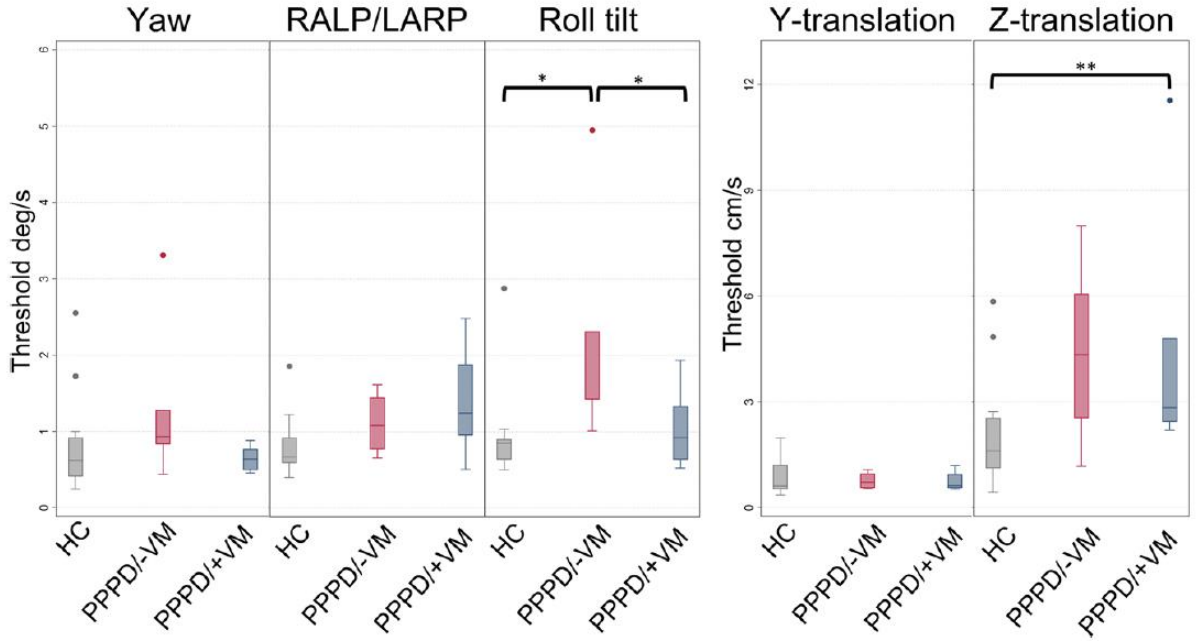


- Patients with vestibular migraine may segregate into two groups reflecting sensitization of brain structures (Lewis et al, 2011a,b; King et al., 2020)

Perception: PPPD



Ricelli et al., 2017

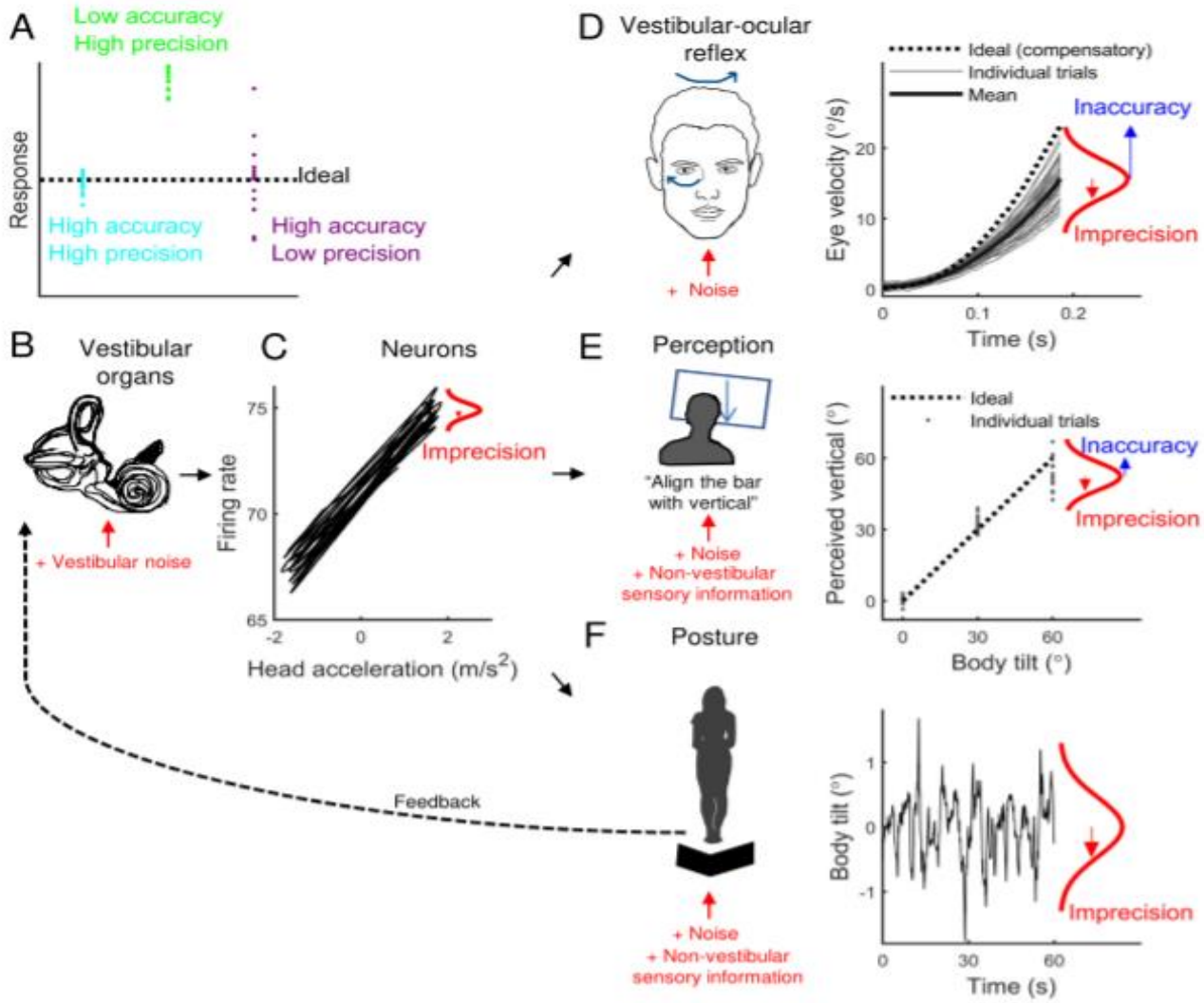


Kobel et al., 2023

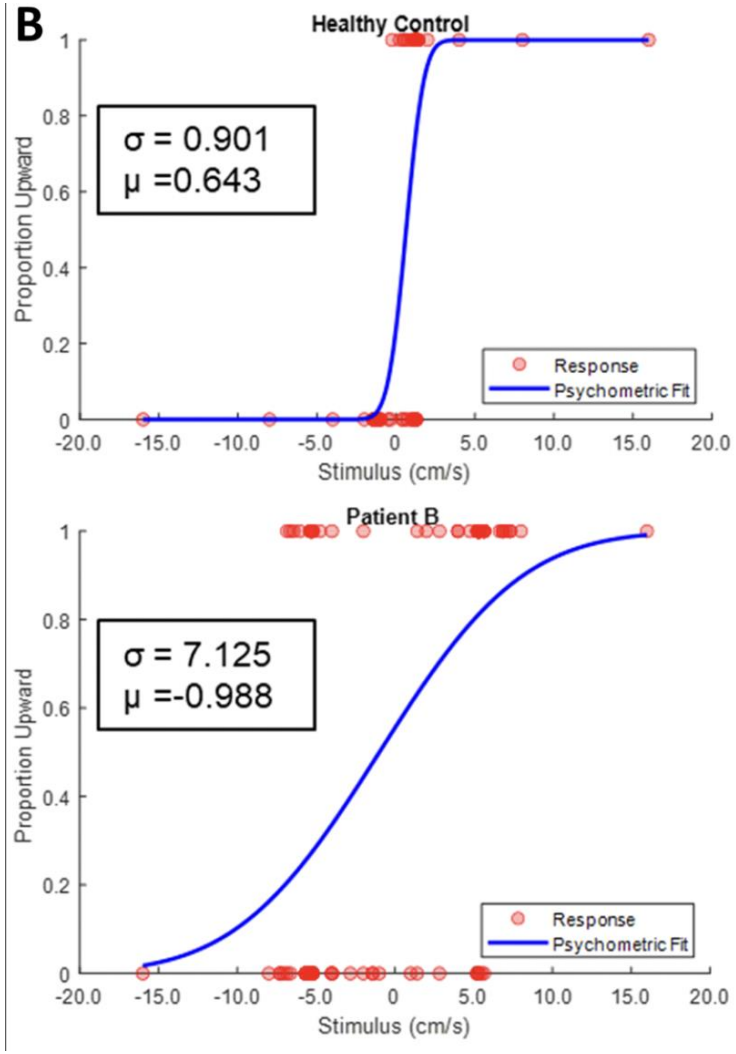
- Patients with PPPD do not display global changes in vestibular perception
- PPPD patients may display large thresholds for motion reliant on understanding gravitational cues

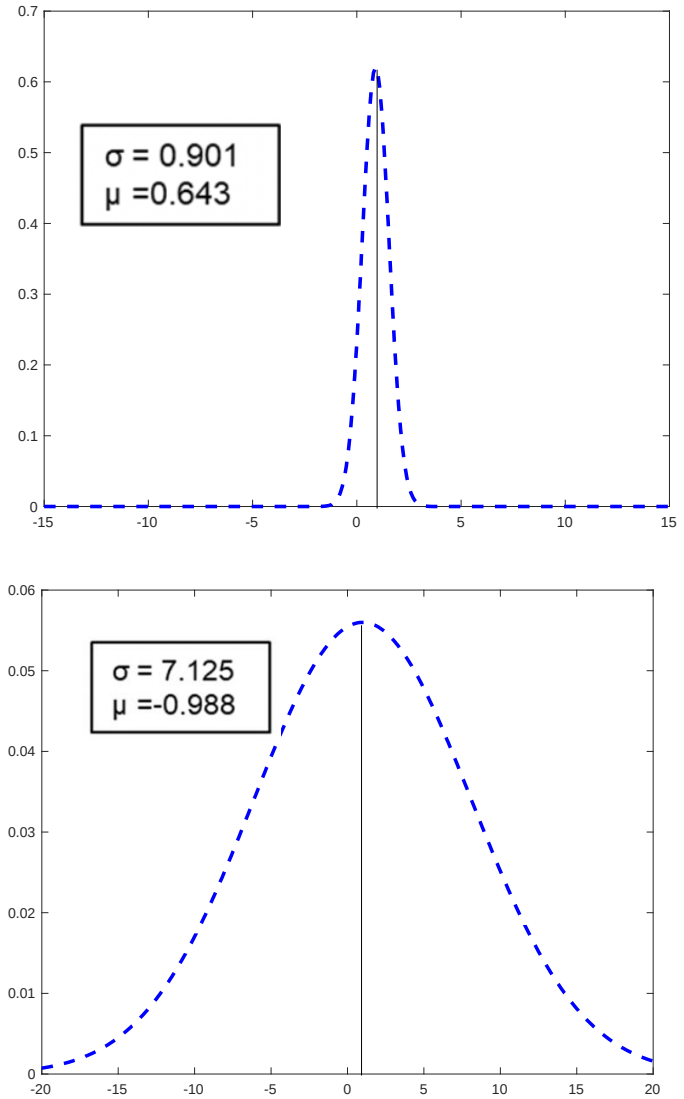
Precision & Accuracy

- **Accuracy**: degree of closeness to a specific value
- **Precision**: closeness of agreement between multiple responses
- Noise in system influences precision
  - Increased noise → large imprecision



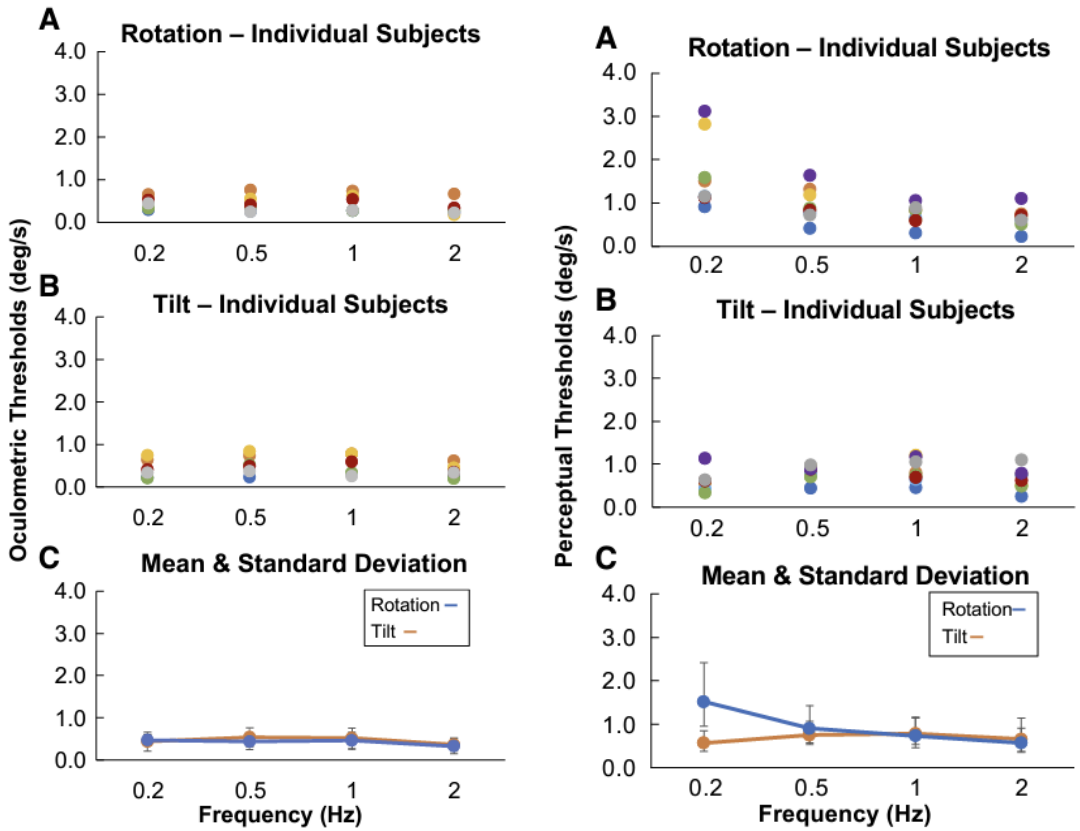
Psychophysics & Perception





- Threshold is proportional to noise in system underlying perception
- Larger threshold = more noise in system

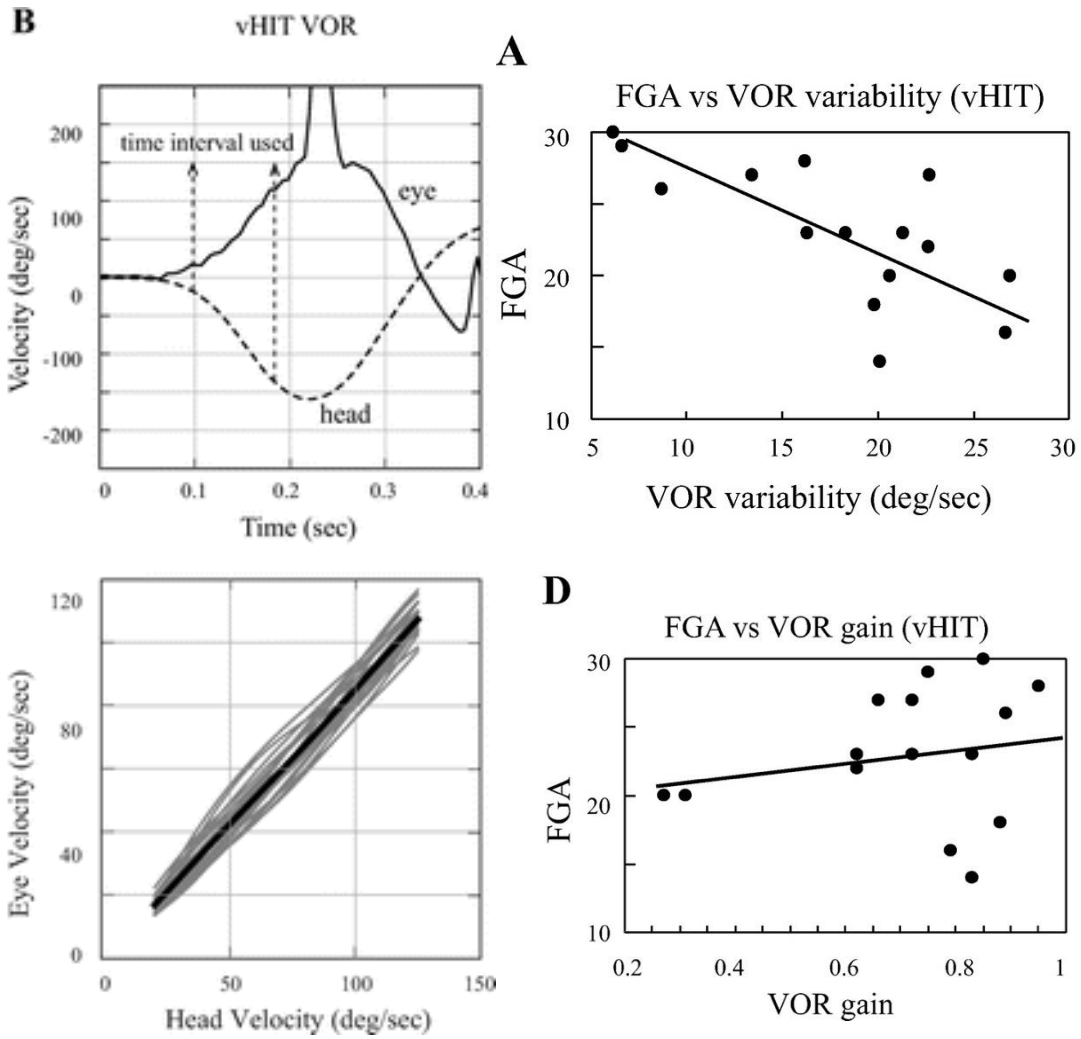
Perception & VOR



Takeda et al., 2023

- Perceptual thresholds and VOR thresholds show different patterns of frequency dependency (Takeda et al., 2024)

VOR Variability & Perception

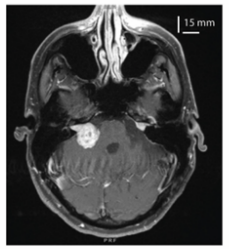


King et al., 2022

- VOR exhibits variability that is velocity dependent (Nouri & Karmali, 2018)
- VOR variability captured during vHIT correlates to functional gait performance in unilateral vestibular schwannoma (King et al., 2022)

VOR Variability & Perception

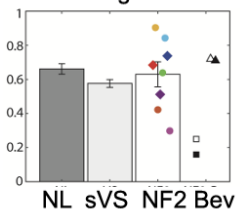
Vestibular schwannoma in *NF2*-related schwannomatosis patient



Adds **neural noise** to afferent vestibular nerve

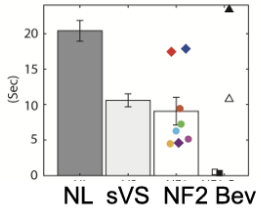
Accuracy

VOR sinusoids – gain



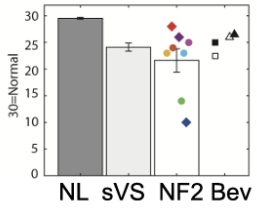
Precision

VOR sinusoids – time constant

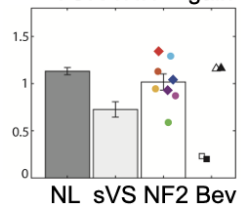


Disability

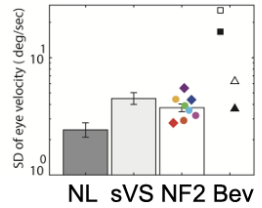
Gait – FGA



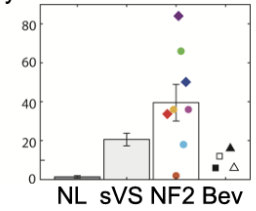
VOR vHIT – gain



VOR vHIT – variability



Dizziness - DHI

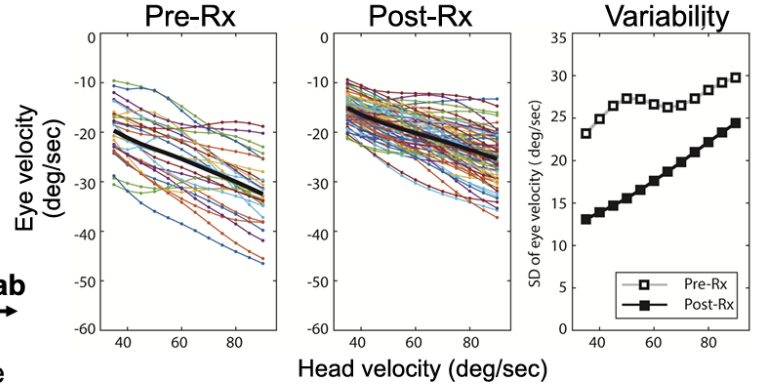


Bevacizumab

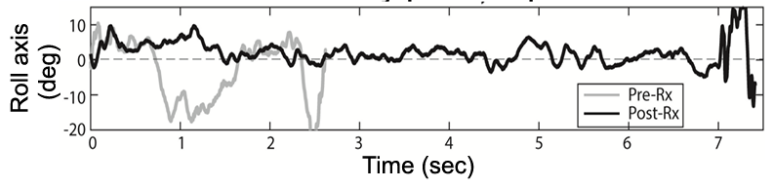
Suppresses neural noise

Abbreviations:
FGA = Functional Gait Assessment
vHIT = vestibular head impulse test
DHI = Dizziness Handicap Inventory
NL = normal
sVS = sporadic vestibular schwannoma
NF2 = *NF2*- related schwannomatosis
Bev = bevacizumab
Rx = therapy with bevacizumab

Vestibulo-ocular reflex (VOR)



Postural sway pre and post-Rx



Madhani et al., 2023

Benefits & Limitations of Vestibular Thresholds

Benefits

- Assess different vestibular end-organs using one methodology
- Well-tolerated
- Direct assay of perception

Limitations & Barriers

- Availability & cost
- Lack of normative data
- Lack of standardization of methodologies
- Lack of understanding of relationships to peripheral function