Vestibular Perception: Rationale & Potential Applications

Megan Kobel, AuD, PhD
Department of Speech, Language, and Hearing Sciences
University of Arizona
mkobel@arizona.edu

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Learning Objectives

- Explain how vestibular perception is measured and the rationale for assessing in patients with dizziness
- Describe changes in vestibular perceptual measures in patients with central and peripheral vestibular disorders
- Discuss how measures of vestibular function may correlate to measures of balance perforamnce

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Outline of Talk

- Vestibular perception: motion discrimination
  - Overview of methodologies
- Motion Discrimination
  - Changes in peripheral loss
  - Changes in aging
  - Changes in central loss
- Vestibular perception: balance
  - Potential correlations in healthy adults and aging
- Spatial Orientation and Verticality Perception
  - Overview of methodologies
  - Changes in peripheral loss and aging
  - Changes in central vestibular disorders
- Vestibular Cognition & Spatial Navigation
  - Overview of methodologies
  - Changes in peripheral loss and aging

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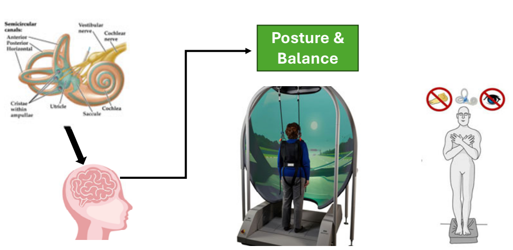
The vestibular system contributes to many functions



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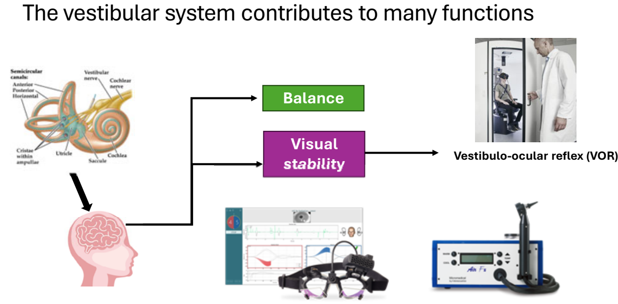

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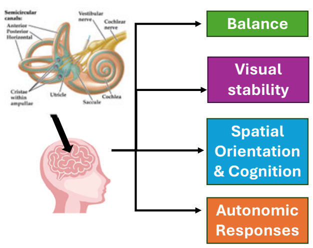
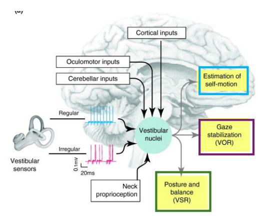
The vestibular system contributes to many functions





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Why study vestibular perception?

- Vestibular perception gives insights into unique pathways (Cullen, 2009).
- Vestibular symptoms defined in terms of sensation and perception (ICVD, 2017)
  - Measures of reflexes do not correlate to function or handicap (Gofrit et al., 2017).
- Vestibular perception may:
  - Identify peripheral and central vestibular pathology
  - Provide information on vestibular function without evoking adverse responses
  - Show changes that correlate to balance performance

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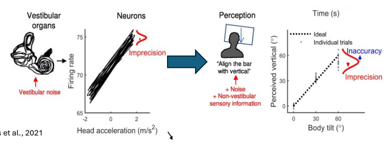
Vestibular Perception: Relationships to noise



Diaz-Artilles et al., 2021

- Current diagnostics focus on **accuracy**: how close to "ideal" a measure is
- **Imprecision** (i.e., variability) related to noise in the sensory system
  - Hair cell noise, afferent noise, vestibular nuclei noise and more
- Measures of vestibular precision may correlate to function and handicap

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Vestibular Perception: Motion Discrimination

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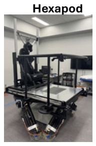
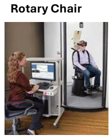
Vestibular Perception: Vestibular Thresholds

Hexapod



Rotary Chair



Motion Simulators

Tilt-Translation Sled

- Quantify individual's sensitivity to passive self-motion cues (Merfeld, 2011)
  - Vision denied, auditory masked, tactile reduced to maximize vestibular contribution

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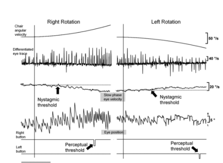
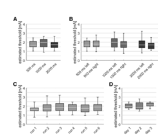
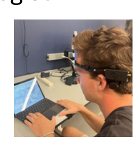
Vestibular Perception: Included Methodologies



Cutfield et al., 2011



Ertl et al., 2018



- Yaw rotation time to response task
  - Yaw acceleration increasing by 0.5 deg/s^2 every three seconds
- Can be done in rotary chair
  - Nystagmus can be measured simultaneously

- Galvanic vestibular stimulation (GVS) thresholds
  - Broad vestibular stimulation
  - Find current level that induces percept of motion

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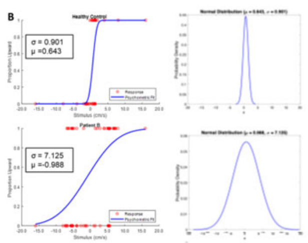
Vestibular Perception: Relationships to noise



- Psychometric curve fit to extract two parameters:
  - **μ** = bias = offset from zero
  - ***σ*** = sigma = width of psychometric function
- One-sigma thresholds proportional to imprecision
  - Thresholds, precision, sensitivity used interchangeably

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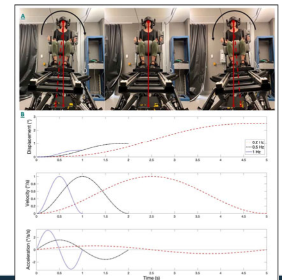
Vestibular Perception: Vestibular Thresholds

- Direction recognition task is the most commonly used methodology
  - Two to twelve interval has been used (Dupuits et al., 2019; van Stiphout et al., 2021)
  - Adaptive staircases typically used for stimulus magnitude selection
  - Stimuli are single cycles of sinusoidal acceleration



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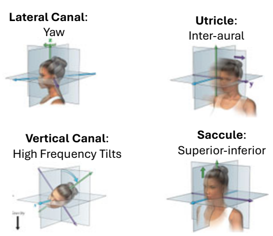
Vestibular Thresholds: Test Batteries

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

Grove et al., 2023



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

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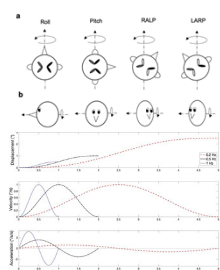
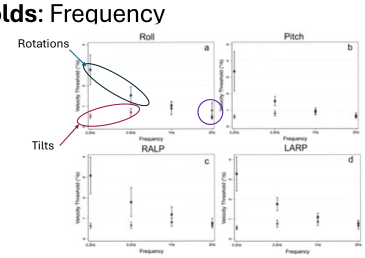
Vestibular Thresholds: Frequency





- Tilt thresholds lower than rotation thresholds at low (<0.5 Hz) frequencies
- Tilt and rotation thresholds equal at high frequencies

Wagner et al., 2022

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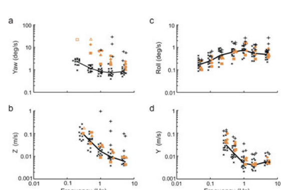
Vestibular Thresholds: Frequency



Priesol et al., 2014

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.

Valko et al., 2012

- In bilateral vestibular ablation, thresholds at lower frequencies show higher elevations suggesting increased vestibular contributions

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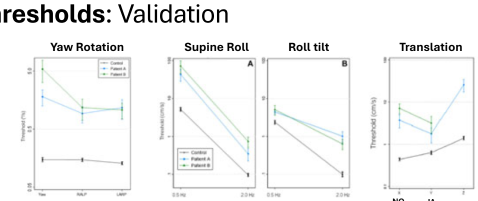
Thresholds: Validation



Kobel et al., 2023; 2024

- Tasks have predominant vestibular contributions (Grabherr et al, 2008; Kobel et al., 2023, 2024)
- Thresholds elevated by ~1.5-84x in complete bilateral ablation (Valko et al., 2012; Kobel et al., 2023, 2024)

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Motion Discrimination: Peripheral Loss

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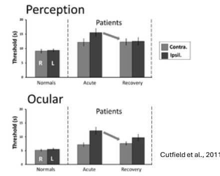
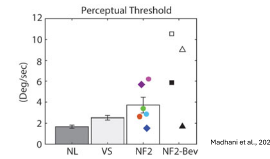
Vestibular Perception: Unilateral Vestibular Loss





- Time to response yaw rotation thresholds elevated in acute UVL patients
  - Greater elevation for ipsi-lesional during acute phase
- Psychometric yaw rotation thresholds elevated in patients with NF-2 (*N* = 5 bilateral, *N* = 3 unilateral) and sporadic unilateral vestibular schwannomas (N=38)

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Thresholds: Localizing Loss

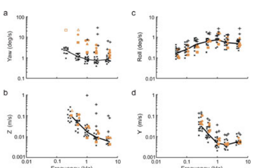

TABLE 2

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

- Patients with horizontal SCC pathology had isolated higher yaw thresholds (Priesol et al., 2014)
- Agrawal et al. (2013) found that oVEMP abnormalities associated with naso-occipital and inter-aural translations
  - cVEMP abnormalities did not correlate to translation thresholds
- Bremova et al (2016) saw correlation only between head-vertical and cVEMPs (Bremova et al., 2016)

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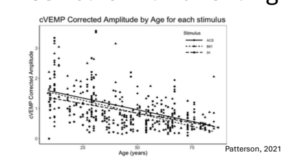
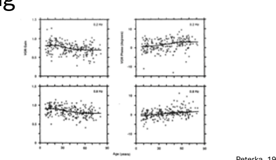
Vestibular Function: Aging





- Loss of hair cells is relatively linear starting at birth but not consistently reflected in testing
- Age-related changes on standard diagnostics variable
  - Calorics, rotary chair, vHIT may show small age-related changes (Peterka, 1990; McGarvie et al., 2015)
  - cVEMPs and oVEMPs sensitive to age (Agrawal et al., 2015; Patterson et al., 2021)

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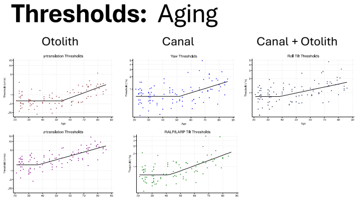
Thresholds: Aging



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

- Across studies, thresholds sensitive to aging (Kobel et al., 2021)
- Largest effects consistently identified for head-vertical thresholds (Bermudez Rey et al., 2016, Gabriel et al., 2022)
- Smallest effects identified for yaw rotation (Roditi & Crane 2021, Chang et al., 2014, Seemungal et al., 2016)

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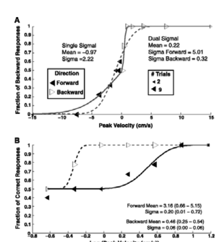
Thresholds & Peripheral Loss: Limitations

- Full characterization of unilateral and bilateral vestibular loss needs to be completed
- Impact of compensation and rehabilitation unknown
- Cannot lateralize pathology
  - May need two independent directional staircases (Roditi & Crane, 2012)



(Roditi & Crane, 2012)

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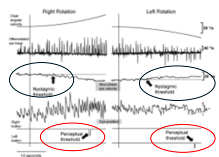
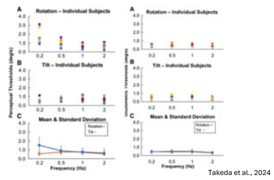
Vestibular Perception & VOR Thresholds


Cutfield et al., 2011


Takeda et al., 2024

- Vestibular perceptual thresholds and VOR thresholds appear to represent unique aspects (Cutfield et al., 2011; Takeda et al., 2024; Chang et al., 2011)
  - VOR thresholds are velocity dependent and not frequency dependent (Takeda et al., 2024; Haburcakova et al., 2012)
  - Supra-threshold perception may correlate to VOR thresholds (Cutfield et al., 2011; Cousins et al., 2014).

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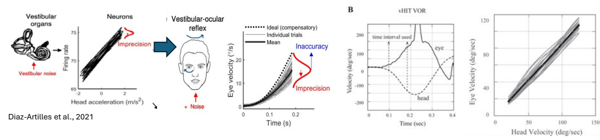
Vestibular Noise: VOR Variability


Diaz-Artilles et al., 2021

- Vestibular noise may also contribute to VOR imprecision
- Increases in vHIT variability seen in vestibular schwannoma patients (King et al., 2022, Mahdani et al., 2024)

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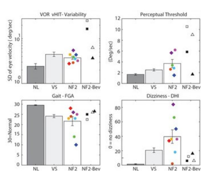
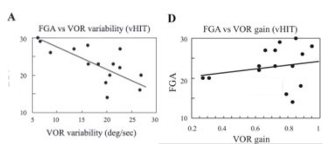
VOR Variability: Potential Applications


Madhani et al., 2024



King et al., 2022

- vHIT variability, thresholds, FGA impairment, and DHI higher in VS patients (Mahdani et al., 2024)
- vHIT variability, but not gain, correlated to FGA and handicap (King et al., 2022).

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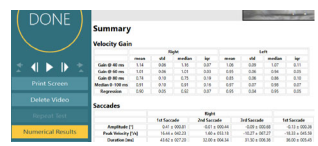
VOR Variability: Measurements



- vHIT gain standard deviation, median, and inter-quartile range provided in software
  - Vital to reduce measurement noise
- Can also quantify using root mean square error of the slow phase eye velocity trace

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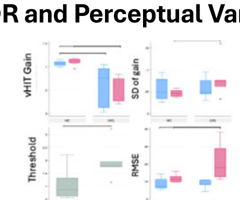
VOR and Perceptual Variability: Associations



	Right Impulses	
	ρ (95% CI)	p
Gain	-0.67 (-0.88, -0.28)	0.040
SD_{gain}	0.32 (-0.13, 0.75)	0.214
RMSE	0.20 (-0.29, 0.70)	0.435
	Left Impulses	
	ρ (95% CI)	p
Gain	-0.66, (-0.97, -0.35)	0.045
SD_{gain}	0.28 (-0.19, 0.84)	0.257
RMSE	0.09 (-0.35, 0.53)	0.727

Kobel et al., In Review

- Both VOR variability and thresholds elevated in UVL
- Thresholds associated to vHIT gain (ρ= -0.672, p=0.004) but no associations between VOR and perceptual variability suggesting unique noise sources

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Vestibular Thresholds: Central Vestibular Disorders

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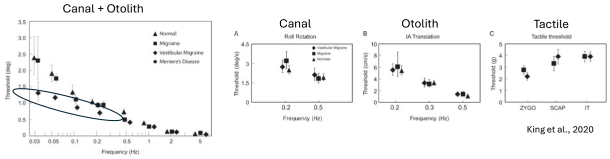
Perception: Vestibular Migraine



King et al., 2020

- Currently, VM remains a clinical diagnosis and there are no objective diagnostic gold standards
- Patients with vestibular migraine show decreased thresholds for motion reliant on canal-otolith integration (Lewis et al, 2011a,b; King et al., 2020)
  - Thresholds correlate to DHI (King et al., 2020)

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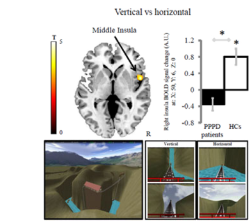
Background: Persistent Postural-Perceptual Dizziness

- PPPD pathophysiology is complex, and several processes likely involved:
  - Altered activity and connectivity in vestibular and visual cortices, hippocampus, and frontal lobes (Indovina et al., 2021)
  - Poor spatial cognition (Breinbauer et al., 2020)
  - **Misperception of motion** (Wurthmann et al., 2021; Yagi et al.2021; Storm et al., 2024; Jáuregui-Renaud et al., 2024)



Ricelli et al., 2017

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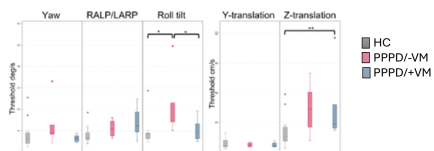
Perception in PPPD: Vestibular Thresholds



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

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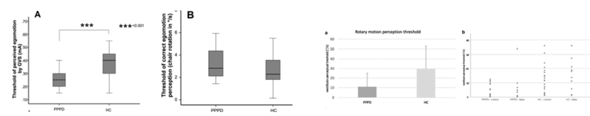
Perception in PPPD: GVS and Time to Response



Storm et al., 2021

Wurthman et al., 2021

- GVS perception thresholds lower in PPPD (Storm et al., 2021; Helmchen et al., 2024)
- Time to response thresholds may or may not be significantly different in PPPD (Storm et al., 2021; Wurthman et al., 2021)

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Vestibular Thresholds: Correlates to Balance

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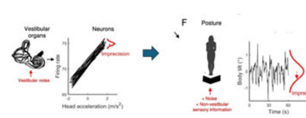
Vestibular Noise: Balance



- Imprecision in postural control may be influenced by vestibular noise
- Balance performance is dependent on sensory input, central integration, and generation of appropriate motor response (Peterka et al, 2019).
- Standard vestibular diagnostic tests show poor correlations to postural control (Jacobson et al., 2011)
  - Ocular counter roll may correlate to mediolateral sway (Serrador et al., 2009)

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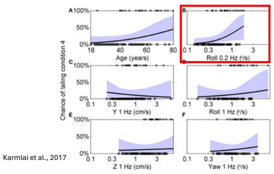
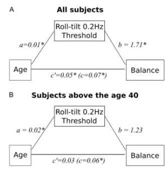
Vestibular Perception: Balance



Karmlai et al., 2017



Beylergil et al., 2019

- Vestibular thresholds associated with ability to complete eyes-closed standing on foam testing (Bermudez Rey et al., 2016; Karmali et al., 2017)
- Roll tilt thresholds partially mediate relationship between age and balance (Beylergil et al., 2019)

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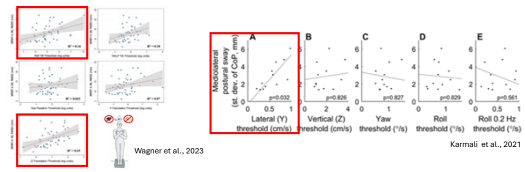
Vestibular Perception: Balance



Wagner et al., 2023

Karmali et al., 2021

- Vestibular thresholds correlated to mediolateral sway (Wagner et al., 2023, 2021; Karmali et al., 2021)
  - Seen for measures with predominant otolith or canal-otolith integration contributions
  - Inconsistent correlations seen for anterior-posterior sway, sway velocity, sway frequency

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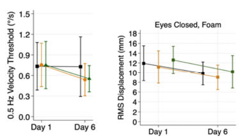
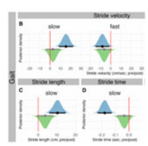
Vestibular Perceptual Learning: Balance



Wagner et al., 2022



Fitze et al., 2024

- Vestibular thresholds can improve with training (Wagner, 2022; 2023; Klaus et al., 2021; Fitze et al., 2024)
- Training associated with reduced sway during quiet stance balance and larger steps and faster walking during gait (Fitze, 2024)

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Spatial Orientation & Verticality

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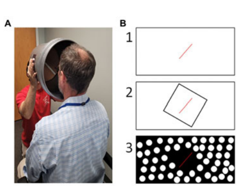
Verticality & Spatial Orientation: Definitions

- **Verticality perception**
  - Dependent on integration of otolith & visual cues
  - Sensitive to vestibular & non-vestibular dysfunction (Detierich et al., 2021)
  - Visual and vestibular weighting can be assessed
- **Spatial orientation**
  - Dependent on integration of vision, vestibular, somatosensory cues, and allocentric spatial cues
  - Variable methodologies used to quantify


Grove et al., 2023

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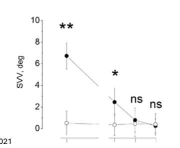
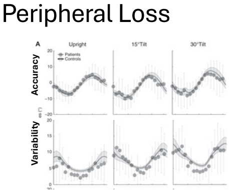
Verticality Perception: Peripheral Loss



Faralli et al., 2021



(Alberts et al., 2016)

- Normative data for SVV accuracy is 2 degrees or less
- Acute UVL can lead to changes in accuracy which normalize in upright testing (Faralli et al., 2021)
- BVL have larger biases and increased variability on visual-vestibular SVV tasks (Alberts et al., 2016)

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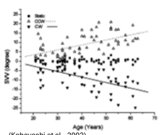
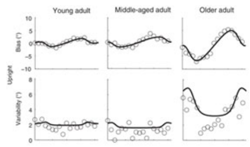
Verticality Perception: Aging


(Kobayashi et al., 2002)


Alberts et al., 2019

- Aging does not lead to static SVV changes in accuracy, but dynamic SVV accuracy may be impacted (Kobayashi et al., 2002)
- Aging may impact SVV precision (Alberts et al., 2019; Razzak et al., 2019)
- Age related changes in otolith function may manifest as increased visual weighting and decreased precision

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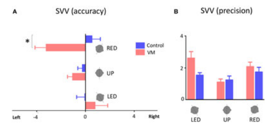
Verticality Perception: Central Vestibular Disorders


Winnick et al, 2021

	Static SVV	
Instrument	Coefficient	p (t Value, df 104)
Symptoms related to unsteadiness	0.21 *	0.02 (2.26)
Spatial Anxiety Scale		
Spatial imagery subscore	0.18	0.057 (1.91)
Spatial navigation subscore	0.22 *	0.02 (2.35)
Spatial mental manipulation subscore	0.14	0.14 (1.47)
Total score	0.18	0.052 (1.96)
Dizziness Handicap Inventory		
Functional subscore	0.22 *	0.01 (2.38)
Physical subscore	0.20 *	0.03 (2.17)
Emotional subscore	0.24 *	0.01 (2.62)
Total score	0.21 *	0.02 (2.29)

Jáuregui-Renaud, 2024

- SVV accuracy in VM patients may be impacted by head tilt (Winnick et al., 2021)
- Higher variability (reduced precision) in SVV seen in patients with PPPD
  - Correlated to sway and spatial anxiety and depersonalization/derealization symptoms

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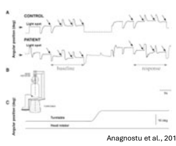
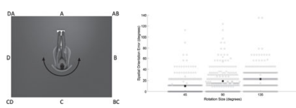
Spatial Orientation: Highlighted Methodologies


Anagnostu et al., 2018


Anson et al., 2021

- For small low frequency rotations (~16°) reorienting are biased in direction rotation (Anagnostou et al., 2018)
  - For larger rotations, average errors are small (~25° or less) (Jáuregui-Renaud et al., 2009; Anson et al., 2023)]
- Errors increase with rotation angle and age (Anson et al., 2021)

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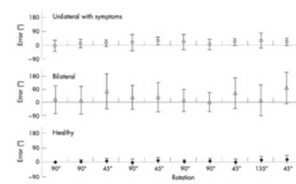
Spatial Orientation: Peripheral Loss & Aging


Jáuregui-Renaud et al., 2009

- Individuals with BVL perform worse than healthy adults but no change seen in unilateral loss (Jáuregui-Renaud et al., 2009; Cohen et al., 2017)
- In aging adults, bilaterally low VOR gain, and bilaterally absent oVEMPs associated with larger spatial orientation errors (Anson et al., 2021)

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Vestibular cognition & Spatial Navigation

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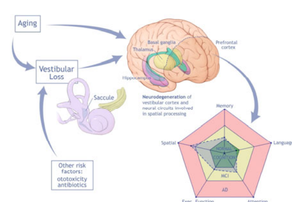
Background: Cognitive and vestibular function


Agrawal et al., 2021

- Growing body of evidence linking cognition and vestibular function
  - Healthy aging (e.g., Bigelow et al., 2015)
  - Vestibular disorders (e.g., Dobbels et al., 2020)
- Strongest links seen for spatial cognition (Agrawal et al, 2020) and for reflexive saccular function (Harun et al., 2017; Pineault et al., 2018; Smith, 2021)

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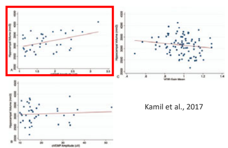
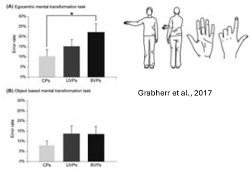
Cognition: Peripheral Loss



Kamil et al., 2017



Grabherr et al., 2017

- Compared to healthy controls, people with UVL or BVL display impaired *attention*, *memory*, and *visual spatial ability*
  - Changes are typically more pronounced in BVH compared to UVH (Popp et al., 2017)
  - Visual spatial changes most commonly reported (Grabherr et al., 2008; Dobbels et al., 2019)
  - Hippocampal volume may significantly differ in people with UVH (Bosmans et al., 2022; Hufner et al., 2007; Jacob et al., 2020; Kamil et al., 2017)

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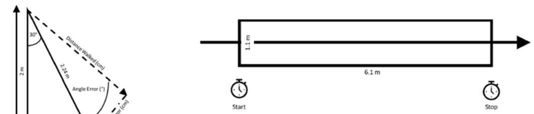
Spatial Navigation: Methodologies



Grove et al., 2021

- Complex sensorimotor skill and often assessed using path integration tasks
- Complex shapes such as the triangle completion test (TCT) or linear paths such as the Gait Disorientation Test (GDT) can be used

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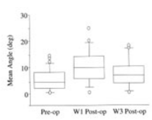
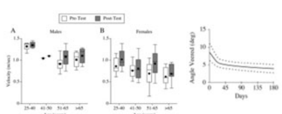
Spatial Navigation: Peripheral Loss



Cohen et al., 2002



Cohen,2002

- Spatial navigation is impaired in vestibular deafferentation (Glasauer et al., 1994; Cohen et al., 2002; Peruch et al. 1994)
  - Partial recovery may occur rapidly (Cohen et al., 2002)
- Spatial navigation training or vestibular rehabilitation does not exhibit consistent improvements (Cohen,2002; Ishikawa, 2020)

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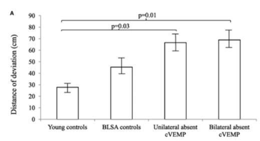
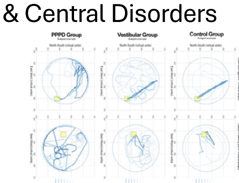
Spatial Navigation: Aging & Central Disorders





- TCT error higher in older adults with unilaterally or bilaterally absent cVEMPs (Anson et al., 2021)
- Spatial navigation is impaired in traumatic brain injury (Padula et al., 2017) and PPPD (Breinbauer et al., 2020)

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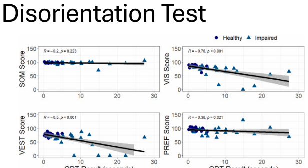
Spatial Navigation: Gait Disorientation Test

Test	Threshold	AUC (95% CI)
GDT	4.5 s	0.910 (0.822-0.998)
FGA1	4.4 s	0.740 (0.584-0.896)
FGA8	7.9 s	0.925 (0.844-1)
FTSTST	8.7 s	0.846 (0.720-0.973)
hDVAT	3 lines lost	0.831 (0.693-0.97)
vDVAT	3 lines lost	0.861 (0.729-0.993)
COMP	75.7	0.932 (0.861-1)
SOM	98.5	0.406 (0.22-0.593)



- Optimal threshold for discriminating between healthy and vestibular-impaired adults using the GDT was 4.5 seconds (Grove et al. 2021)
- GDT is moderately to strongly associated with balance in challenging sensory condition (Grove et al. 2025)

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Vestibular Thresholds: Cognition

TABLE 2. Spearman rank correlation coefficients for each log-transformed vestibular threshold and assessments of cognition and path integration

	DSST n = 50		TMT-A n = 50		TMT-B n = 50		GDT n = 45	
	r_s	p	r_s	p	r_s	p	r_s	p
Yaw rotation	−0.228	0.574	0.238	0.499	0.205	0.784	0.298	0.234
RALP/LARP tilt	**−0.553**	**0.001**	0.336	0.138	0.374	0.068	**0.466**	**0.012**
Roll tilt	**−0.537**	**0.001**	0.355	0.062	**0.369**	**0.045**	0.161	0.999
Y-translation	−0.359	0.057	0.358	0.058	0.306	0.161	**0.416**	**0.023**
Z-translation	**−0.754**	**<0.001**	**0.547**	**<0.001**	**0.606**	**<0.001**	0.278	0.321

Kobel et al., 2025

TABLE 4. Results of individual linear regression models adjusting for age

	β_{std}	*t*-Stat	p
DSST (n = 50)			
Yaw rotation	−0.051	−0.499	1.00
RALP/LARP tilt	−0.099	−0.690	1.00
Roll tilt	−0.258	−2.477	0.085
Y-translation	0.061	0.522	1.00
Z-translation	**−0.377**	**−2.932**	**0.025**
TMT-B (n = 50)			
Yaw rotation	−0.026	−0.225	1.00
RALP/LARP tilt	−0.108	−0.716	1.00
Roll tilt	0.081	0.662	1.00
Y-translation	−0.088	−0.671	1.00
Z-translation	**0.219**	**2.073**	**0.044**
GDT (n = 45)			
Yaw rotation	0.191	1.314	0.980
RALP/LARP tilt	0.299	1.638	0.550
Roll tilt	−0.023	−0.151	1.00
Y-translation	**0.469**	**2.883**	**0.030**
Z-translation	−0.317	−1.748	0.440

Six participants could not complete RALP/LARP thresholds, thus these results reflect data

- Thresholds reflecting otolith or canal-otolith integration associated to multiple cognitive measures
- Modality specific changes in vestibular perception correlate to cognition in healthy adults (20-84 years)

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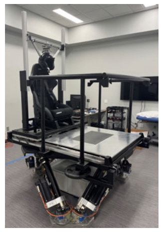
Vestibular Perception: Summary

- Vestibular perception can be broadly assessed including:
  - Vestibular thresholds
  - Verticality perception
  - Spatial orientation
  - Spatial navigation
- Vestibular perception is:
  - Sensitive to peripheral and central vestibular disorders
  - Correlated to balance performance
  - Correlated to cognitive performance
- Vestibular precision (perception, VOR, balance) may provide unique insights into function



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  - Andrew Wagner, PhD, DPT (Creighton)
  - Daniel Merfeld, PhD (Ohio State)
  - Colin Grove, PhD, DPT (Emory)
  - Brian Loyd, PhD DPT (Montana State)

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