Estimating Vestibular Perceptual Thresholds using a Six-Degree-of-Freedom Motion Platform

Matthias Ertl[1], **Daniel C. Fitze**[1], **Gerda Wyssen**[1], **Fred W. Mast**[1]

[1] Institute of Psychology, University of Bern

Corresponding Author

Matthias Ertl
matthias.ertl@unibe.ch

Citation

Ertl, M., Fitze, D.C., Wyssen, G., Mast, F.W. Estimating Vestibular Perceptual Thresholds using a Six-Degree-of-Freedom Motion Platform. *J. Vis. Exp.* (186), e63909, doi:10.3791/63909 (2022).

Date Published

August 4, 2022

DOI

10.3791/63909

URL

jove.com/video/63909

Abstract

Vestibular perceptual thresholds refer to the motion intensity required to enable a participant to detect or discriminate a motion based on vestibular input. Using passive motion profiles provided by six degree-of-motion platforms, vestibular perceptual thresholds can be estimated for any kind of motion and thereby target each of the sub-components of the vestibular end-organ. Assessments of vestibular thresholds are clinically relevant as they complement diagnostic tools such as caloric irrigation, the head impulse test (HIT), or vestibular evoked myogenic potentials (VEMPs), which only provide information on sub-components of the vestibular system, but none of them allow for assessing all components. There are several methods with different advantages and disadvantages for estimating vestibular perceptual thresholds. In this article, we present a protocol using an adaptive staircase algorithm and sinusoidal motion profiles for an efficient estimation procedure. Adaptive staircase algorithms consider the response history to determine the peak velocity of the next stimuli and are the most commonly used algorithms in the vestibular domain. We further discuss the impact of motion frequency on vestibular perceptual thresholds.

Introduction

The human vestibular end-organ consists of five components, each optimized for detecting a specific component of the natural motion spectrum. The three semicircular canals are oriented roughly orthogonal to each other, which allows them to detect head rotations around three axes. The canals are accompanied by two macula organs for the registration of translational accelerations along the vertical axis or in the horizontal plane[1]. A functional decline or loss in each of the five components can lead to severe symptoms such as dizziness, vertigo, imbalance, and an increased risk of falling[2]. However, objectively assessing the function of all components separately is a laborious task and requires multiple assessments[3]. For example, the state of the horizontal canal is typically assessed through caloric irrigation and the head impulse test (HIT). The current gold standard for assessing the macula organs is vestibular evoked myogenic potentials (VEMPs). By combining multiple assessments, clinicians arrive at a more complete picture of the vestibular state from which they can derive diagnosis and treatment options.

A promising approach for quantifying vestibular performance is vestibular perceptual thresholds, which provide an objective, quantitative measure of the lowest self-motion intensity that can be reliably detected or discriminated by a participant. Even though perceptual threshold procedures are well established in some clinical disciplines (e.g., audiology), perceptual vestibular thresholds are not yet used for diagnostic purposes in the vestibular domain[4]. One reason for this is the non-availability of motion platforms and easy-to-use software. In principle, motion platforms and rotatory chairs can be used for threshold estimation. However, while six-degree-of-freedom (6DOF) motion platforms are suitable for estimating thresholds for various motion profiles, enabling the investigation of all five sub-components of the vestibular organ, rotatory chairs can only be used for accessing rotations in the horizontal (yaw) plane[1,4].

Vestibular thresholds are typically estimated for translations along the three main axes (naso-occipital, inter-aural, head-vertical) and for rotations around them (yaw, pitch, roll), as visualized in **Figure 1**. Vestibular perceptual thresholds also depend on the stimulus frequency[5]. To account for this, motion profiles with a sinusoidal acceleration profile, consisting of a single frequency, are most often used for threshold estimation, but other profiles[6,7,8] have also been used in the past.

Vestibular perceptual thresholds provide a tool for studying the interaction between vestibular sensation and higher cognitive processes. Thresholds, therefore, supplement clinical assessments such as the HIT, caloric irrigation, and vestibular evoked potentials, which rely on mechanisms (reflex arcs) bypassing the cortex. Additionally, vestibular perceptual thresholds estimated on a motion platform assess vestibular function in an ecologically valid setting[9], rather than using artificial stimulation, which introduces multi-sensory conflicts[1].

Due to the bidirectional nature of vestibular stimuli[10], it is common to estimate vestibular discrimination rather than detection thresholds[4]. During a discrimination task, the participant perceives a stimulus and must decide which category it belongs to. For example, participants must decide in which direction they are moved (e.g., left/right). The theoretical framework for the threshold estimation is signal detection theory[10,11]. Discrimination thresholds can be estimated using various approaches, but in the vestibular domain, adaptive staircase procedures are the standard. In an adaptive staircase procedure, the intensity, typically the peak velocity, of the subsequent movement depends on the participants' response (correct/incorrect) to the last stimulus/stimuli. Adaptive staircase procedures can be implemented in many ways[12], but the most frequently used algorithm in vestibular research is x-down/y-up procedures with fixed step sizes. For example, in a three-down/one-up staircase, the stimulus intensity is reduced after the participant has given correct answers in three subsequent trials, but the intensity is increased whenever an incorrect answer has been provided (**Figure 2**). The exact selection of x and y in a x-down/y-up staircase enables one to target different threshold values (percentage of correct responses)[13]. A three-down/one-up staircase targets the intensity where participants correctly respond in 79.4% of the trials. Besides adaptive staircase procedures, other studies[14] have used predefined, fixed intensities for threshold estimations. Using fixed intensities allows for estimating the whole psychometric function, which contains a lot more information than a single threshold value. However, fixed intensity procedures are time-consuming and less efficient when only a specific threshold value is of interest.

This article describes a protocol for estimating vestibular recognition thresholds using a 6DOF motion platform and an adaptive staircase procedure.

Protocol

All data used for this manuscript were recorded after participants gave their informed consent and in line with the ethics approval of the Faculty of Human Sciences of the University of Bern [2020-04-00004].

1. Materials

1. In order to estimate vestibular perception thresholds, ensure that there is access to a motion platform or a rotatory chair.
2. Ensure that a control software for programming the motion profiles and interfacing the motion platform is present.

   NOTE: PlatformCommander[15,16], an open-source software package to interface the motion platform, was used in this study. PlatformCommander allows for defining sinusoidal acceleration profiles, which are often used to estimate vestibular thresholds.
3. Ensure that a response device, for example, a game controller, is present for registering the participants' responses.
4. Motion platforms produce noise correlated with the movement intensity. Participants can use this auditory noise as an additional, unintended source of information during the estimation of vestibular perception thresholds. To mask the sound of the platform, present the participants with white noise *via* noise-canceling headphones during each trial.
5. Blindfold the participants to eliminate the influence of visual motion cues.
6. Decide on which estimation algorithm to use and define the respective parameters. If a staircase approach is used, define the starting point, the step size, the up-date, and termination rules. If the user does not know what values to choose, perform pilot measurements or consult the literature. Defaults are provided by the example scripts available online (https://gitlab.com/dr_e/2022-jovedemo).

   NOTE: The starting point defines the peak velocity of the platform in the first trial. Determine suitable starting velocities by pilot testing or by consulting the threshold literature (for yaw thresholds, see Grabherr et al.[5]). The step size describes by how much the intensity changes between trials. The up-date rule describes whether and how the stimulation intensity is changed based on the participants' responses. In the vestibular domain, a three-down/one-up staircase procedure is common. This means that the intensity is decreased after three consecutive correct answers but increased after each wrong answer. The termination criteria are usually defined by either a fixed number of trials or the number of intensity reversals. Intensity reversals are trials in which the response causes an intensity increase after one or more intensity decreases or vice versa. The provided script keeps track of the reversals, terminates the procedure, and automatically calculates the final threshold value.
7. Decide for which frequency the threshold needs to be estimated. In the demonstration, 1 Hz was used.

NOTE: Vestibular thresholds are typically investigated for frequencies between 0.1 and 5 Hz, and thresholds are known to decrease as stimulation frequency increases[3].

8. Decide for which type of motion the threshold needs to be estimated. In the demonstration, yaw rotations are performed.

   NOTE: Thresholds can be estimated for translations and rotations. Thresholds are most often estimated for the three main axes (naso-occipital, inter-aural, head-vertical) and the rotations around them (roll, pitch, yaw). The provided script only estimates one defined motion (direction, frequency) at a time. However, for estimating multiple thresholds, the script can be rerun with the same or different motion parameters (direction, frequency, rotation axes).

9. Start every threshold estimation procedure with training, allowing the participant to familiarize themselves with the task. Use the script "threshold-training.jl" available online (see step 1.6) for this purpose.

   NOTE: The training script presents a series of supra-threshold motion stimuli. The test script automatically controls the estimation procedure, handles the staircase algorithm updating, the stimulus intensity, the presentation of the motion stimulus, the presentation of auditory white noise during each motion stimulus, as well as the logging of all relevant data. During the training, ensure that the participant understands the task and provide guidance in case of uncertainties.

2. Instructions

1. Explain the experimental procedure to the participant and obtain informed consent.
2. Seat the participant on the chair mounted on the motion platform.
3. Secure the participant using seat belts.
4. Give the response buttons to the participant and explain how the keys are assigned to the responses.
5. Blindfold the participant. Position the headphones on the participant's head.
6. Apply a proper head fixation.
7. Turn on the motion platform using the main, battery, and controller switch.
8. Ensure that the area around the platform is clear and that no people can approach the moving platform during the test.
9. Start the training procedure script by typing **julia threshold-training.jl** into the command line.
10. Inform the participant about the engagement of the motion platform.
11. Ensure a successful initialization of the session by checking the status displayed in the GUI of the server software (PlatformCommander). When successfully initialized, the status display will switch from **Session Not Underway** to **Short Sequence**. It will also display the IP address of the connected client and the time when the session was initialized. If the session is not successfully initialized after a few seconds, check the network connection between the client and the server. Ensure that the motion platform is switched on and that the controller is connected.
12. Ensure that the participant understands the task, point out mistakes by the participant (e.g., when they push the wrong buttons), and respond to potential questions the participant may have.

13. Inform the participant that the training procedure is finished, and the estimation procedure is about to start.
14. Start the estimation procedure script by typing **julia threshold-test.jl** into the command line.
15. Supervise the fully automated estimation procedure until the termination criteria are reached.
16. Depending on the design, repeat the procedure starting at step 2.13 using different stimuli or terminate the procedure.
17. Park the motion platform.
18. Remove the head fixation, headphones, blinder, and buttons, and let the participant descend.
19. Debrief the participant about the procedure and ask them about their experience to improve further experiments.
    NOTE: The procedure can be paused and then restarted at any time, preferably not during the threshold estimation phase (steps 2.15-2.17).

Representative Results

The result of the described procedure is a graph showing the used stimulus intensities over trials (**Figure 2**). The intensities should converge toward a constant value (**Figure 2**, dashed line). The adaptive staircase procedure links an acceleration intensity to the motion perception of the participant. The threshold is typically calculated by the test script (e.g., threshold-test.jl) as the mean value of all or a subset of the intensities presented at reversal trials. No further processing of the obtained value is necessary. Depending on the used update rule, different points on the psychometric function can be targeted. Using the three-down/one-up rule, the intensity at which the participant gives the correct response in 79.4% of the trials is estimated.

Figure 3 visualizes a failed threshold estimation. In the example, the termination criteria were set to 30 trials instead of a sufficient number of reversals. Due to the early mistake (trial 11), the estimation procedures resulted in a poor threshold estimation, which can be recognized by the fact that the staircase did not converge toward a value but kept a monotonic decrease until the end.

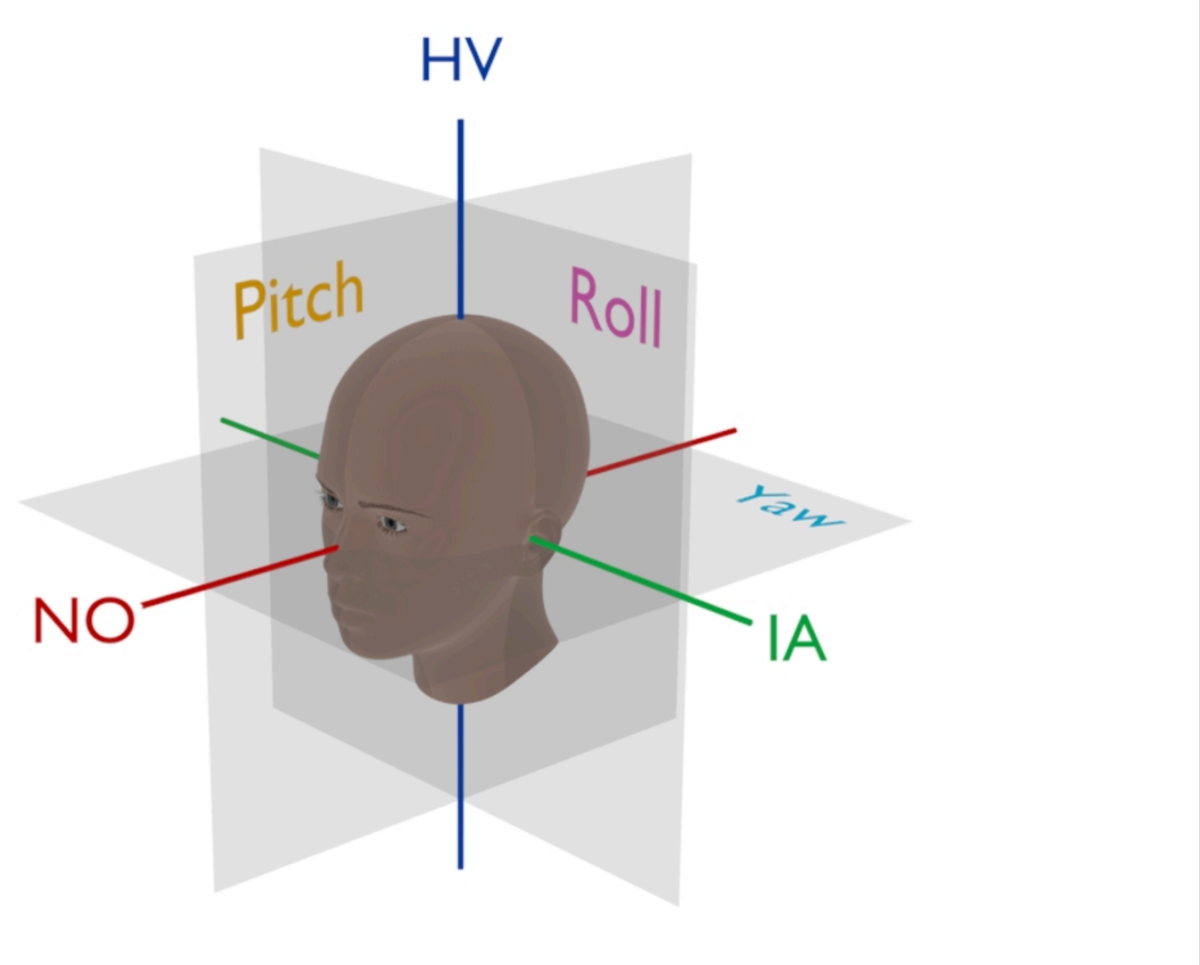

Figure 1: Visualization of the main axes and planes. The visualized axes and planes are typically used to describe motions related to head movements. Vestibular perceptual thresholds are most often estimated for the naso-occipital (NO), inter-aural (IA), and head-vertical (HV) axes, and for rotations around them which are referred to as yaw, pitch, or roll rotations. The figure was created using a freely available 3D head model[17]. Please click here to view a larger version of this figure.

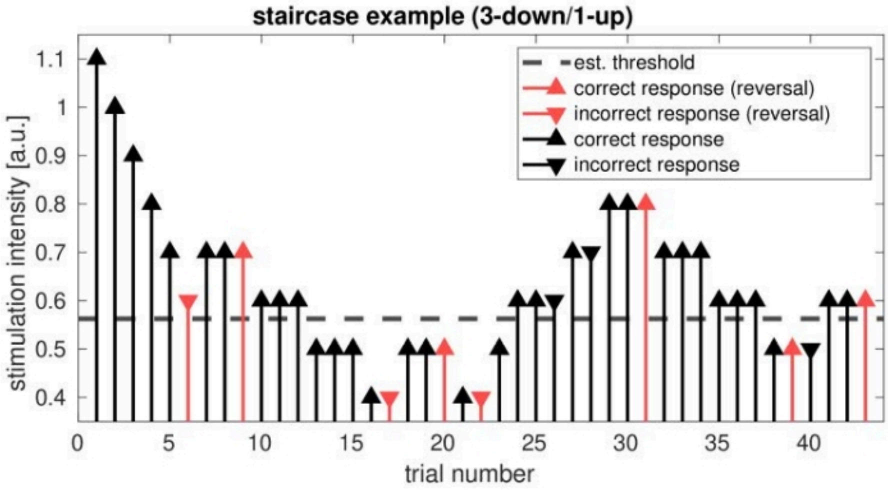

Figure 2: Visualization of a three-down/one-up staircase procedure. Intensity reversals are visualized in red. Triangles pointing up represent trials with correct responses, and triangles pointing down represent trials with incorrect responses. The dashed line represents the estimated threshold, which was calculated as the mean value of all eight reversal intensities. In the beginning, the update rule follows a one-down pattern until the first reversal (trial 6). This allows for a more efficient threshold estimation, particularly in cases where the start intensity is large compared to the unknown threshold. Please click here to view a larger version of this figure.

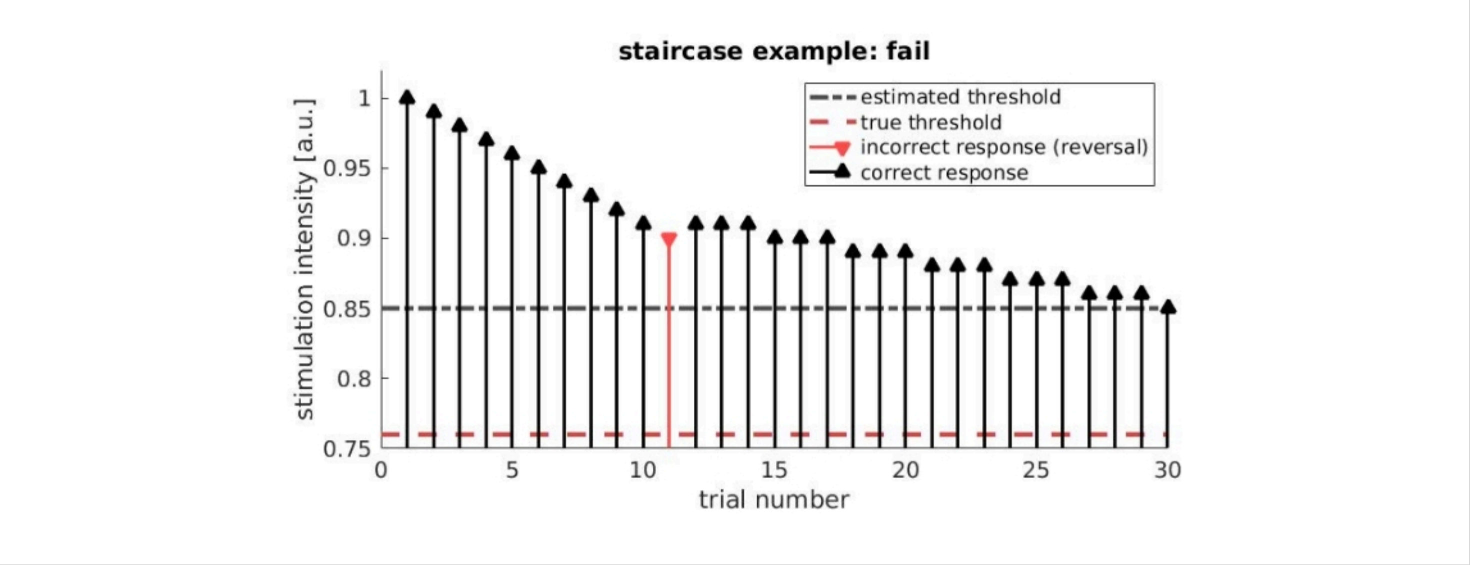

Figure 3: Visualization of a failed threshold estimation. Due to the termination criteria (30 trials) and a selected start intensity relatively far away from the true threshold, the staircase function did not converge. A faster convergence toward the true threshold is hindered by an early, false response (trial 11). Please click here to view a larger version of this figure.

Discussion

The presented protocol allows for a reliable and efficient estimation of vestibular perceptual thresholds. The protocol is suitable for threshold estimation along and around arbitrary axes and can be applied for all relevant stimulus frequencies (e.g., 0.1-5 Hz). Although we present data using a standard three-down/one-up adaptive staircase procedure, the protocol can also be used for other, more efficient estimation procedures[12], including fixed intensity, transformed/weighted up/down, or Bayesian (e.g., Quest[18]) approaches. An exhaustive discussion of the available algorithms is beyond the scope of the presented manuscript, but an excellent comparison of theory, simulations, and actual data can be found elsewhere[19]. Efficient estimation procedures are of great relevance in the clinical context, where the time is limited, and research on faster assessments is currently conducted[19,20].

A promising field of research is the identification of particular motion profiles and other clinically relevant parameters such as balance[2,21]. This line of research is important as it provides guidance on which axes and frequencies are most predictable for clinically relevant behavior and events, such as the risk of falling, thereby reducing the search space in a clinical context.

Once the equipment and software are available and work as intended, two factors are critical for reliable threshold estimation. First, the experimenter must ensure that the participant understands the task and stays vigilant throughout the entire procedure. For most stimuli (e.g., all translations), the instructions are clear and easy to follow. However, for pitch and roll rotations, the instruction to answer with left or right can be ambiguous, especially when the axis of rotation is placed at head level. In these cases, the body parts above the rotation axes (e.g., head) rotate in the opposite direction than the body parts below the rotation axes (e.g., feet). The terms left/right can be ambiguous, and it might be helpful to ask the participants to classify motions as clockwise or counterclockwise. It is important to explain and practice how the participant is expected to judge the motion stimuli. A sufficient number of test trials is particularly important when patients or older adults are investigated.

Second, it is important to choose a sufficient number of trials around the threshold. We recommend an adaptive termination criterion as the number of intensity reversals, instead of a fixed number of trials which has been used by others[7,22]. Additionally, using a predefined number of trials can become inefficient and bears the risk that the staircase does not converge when the start intensity is too far away from the threshold. In general, pilot experiments are required to select reasonable starting intensities and termination criteria.

Staircase algorithms aim to estimate a single point on the psychometric function[23,24]. Therefore, they provide limited information because response biases and the slope of the psychometric function cannot be derived from the estimated threshold. If such parameters are of interest, fixed intensities can be used to sample over a larger interval, allowing to fit the psychometric function. Although such a procedure is more time-consuming, it allows for more sophisticated analyses that can provide valuable insights[14,25]. Alternatively, adaptive slope-estimation algorithms can be used[13].

An important aspect in the estimation of vestibular perception thresholds is the minimization of cues from other sensory systems. To achieve this, the noise generated by the platform is typically masked by white noise. The minimization of proprioceptive or tactile cues is more challenging[1], and can only partly be achieved because acceleration requires a force acting on the body, which will inevitably induce extra-vestibular stimulation. However, cushions are often used to reduce tactile and proprioceptive signals. Likewise, the head fixation is required to ensure a constant orientation of the vestibular organs relative to the motion and to ensure that the motion profile performed by the head is the same as the one by the platform, without any filtering by the body that occurs under unrestricted motion conditions[26].

At this point in time, vestibular perceptual thresholds are predominantly used in basic research. Studies showed that vestibular thresholds increase with age[27,28], and they depend on direction[20,28] and the frequency of motion[5,29]. More recently, perceptual thresholds were used to document the first evidence of perceptual learning in the vestibular domain[14].

Studies comparing patients with vestibular disorders to healthy controls showed altered vestibular perceptual thresholds in line with their pathology. For example, thresholds were increased in patients with vestibular failure[29,30,31,] and a tendency to reduced thresholds or even a hypersensitivity was shown in patients with vestibular migraine[31,32]. These studies imply the potential for clinical applications, and a recent review[4] discussed the applicability and usefulness of vestibular perceptual thresholds in a clinical diagnosis. One important aspect is that perceptual thresholds add unique properties to the doctor's toolbox. The standard procedures (HIT, VEMP, caloric irrigation) use direct pathways from the vestibular end-organs to the muscles of the eyes or cervix. Thereby, they do not offer the possibility of investigating the information chain to the neo-cortex. The estimation of vestibular perceptual thresholds, on the other hand, includes cognitive processes allowing to test the vestibular system from a different angle, which might be particularly interesting in the context of persistent postural-perceptual dizziness (PPPD). A shortcoming of the presented procedure is its inability to detect directional asymmetries, which has been reported by others[33].

Vestibular perceptual thresholds are also of interest in the evaluation and monitoring of (therapeutic) interventions. Many studies use the risk of falling as an endpoint in the evaluation of treatment effectiveness. However, since a correlation between vestibular thresholds about the roll axis and risk of falling[2] and performance during balance tasks[34] has been demonstrated, thresholds could be used as a more reliable dependent variable, for example, to assess the outcome[35] or optimal configuration of vestibular implants.

Disclosures

The authors have no competing interests.

Acknowledgments

We are grateful for the support provided by Carlo Prelz from the Technology Platform of the Human Sciences Faculty. We thank Noel Strahm for his contribution to the staircase implementation.

References

1. Ertl, M., Boegle, R. Investigating the vestibular system using modern imaging techniques-A review on the available stimulation and imaging methods. *Journal of Neuroscience Methods.* **326**, 108363 (2019).
2. Beylergil, S. B., Karmali, F., Wang, W., Bermúdez Rey, M. C., Merfeld, D. M. Vestibular roll tilt thresholds partially mediate age-related effects on balance. *Progress in Brain Research.* **248**, 249-267 (2019).
3. Brandt, T., Dieterich, M., Strupp, M. *Vertigo and Dizziness.* Springer, London (2013).
4. Kobel, M. J., Wagner, A. R., Merfeld, D. M., Mattingly, J. K. Vestibular thresholds: A review of advances and challenges in clinical applications. *Frontiers in Neurology.* **12**, 643634 (2021).
5. Grabherr, L., Nicoucar, K., Mast, F. W., Merfeld, D. M. Vestibular thresholds for yaw rotation about an earth-vertical axis as a function of frequency. *Experimental Brain Research.* **186** (4), 677-681 (2008).
6. Seemungal, B. M., Gunaratne, I. A., Fleming, I. O., Gresty, M. A., Bronstein, A. M. Perceptual and nystagmic thresholds of vestibular function in yaw. *Journal of Vestibular Research: Equilibrium and Orientation.* **14** (6), 461-466 (2004).
7. Gianna, C., Heimbrand, S., Gresty, M. Thresholds for detection of motion direction during passive lateral whole-body acceleration in normal subjects and patients with bilateral loss of labyrinthine function. *Brain Research Bulletin.* **40** (5-6), 443-447 (1996).
8. Soyka, F., Robuffo Giordano, P., Beykirch, K., Bülthoff, H. H. Predicting direction detection thresholds for arbitrary translational acceleration profiles in the horizontal plane. *Experimental Brain Research.* **209** (1), 95-107 (2011).
9. Ertl, M. et al. The cortical spatiotemporal correlate of otolith stimulation: Vestibular evoked potentials by body translations. *NeuroImage.* **155** (September 2016), 50-59 (2017).
10. Merfeld, D. M. Signal detection theory and vestibular thresholds: I. Basic theory and practical considerations. *Experimental Brain Research.* **210** (3), 389-405 (2011).

11. Kay, S. M. *Fundamentals of Statistical Signal Processing: Detection Theory.* Prentice-Hall PTR. (1998).

12. Kingdom, F. A. A., Prins, N. *Psychophysics: A Practical Introduction.* Academic Press. (2016).

13. Leek, M. R. Adaptive procedures in psychophysical research. *Perception & Psychophysics.* **63** (8), 1279-1292 (2001).

14. Klaus, M. P. et al. Roll tilt self-motion direction discrimination training: First evidence for perceptual learning. *Attention, Perception & Psychophysics.* **82** (4), 1987-1999 (2020).

15. Ertl, M., Prelz, C., Fitze, D. C., Wyssen, G., Mast, F. W. PlatformCommander-An open source software for an easy integration of motion platforms in research laboratories. *SoftwareX.* **17**, 100945 (2022).

16. Ertl, M., Prelz, C., Fitze, D. C., Wyssen, G., Mast, F. W. Manual PlatformCommander Version 0.9. (2021).

17. Rihs, M., Fitze, D. C., Ertl, M., Wyssen, G., Mast, F. W. 3D Models of 6dof motion. at <https://zenodo.org/record/6035612> (2022).

18. Watson, A. B., Pelli, D. G. QUEST: A general multidimensional Bayesian adaptive psychometric method. *Perception & Psychophysics.* **33** (2), 113-120 (1983).

19. Karmali, F., Chaudhuri, S. E., Yi, Y., Merfeld, D. M. Determining thresholds using adaptive procedures and psychometric fits: evaluating efficiency using theory, simulations, and human experiments. *Experimental Brain Research.* **234** (3), 773-789 (2016).

20. Dupuits, B. et al. A new and faster test to assess vestibular perception. *Frontiers in Neurology.* **10**, 707 (2019).

21. Karmali, F., Rey, M. C. B., Clark, T. K., Wang, W., Merfeld, D. M. Multivariate analyses of balance test performance,vestibular thresholds, and age. *Frontiers in Neurology.* **8**, 578 (2017).

22. Keywan, A., Wuehr, M., Pradhan, C., Jahn, K. Noisy galvanic stimulation improves roll-tilt vestibular perception in healthy subjects. *Frontiers in Neurology.* **9**, 83 (2018).

23. Wichmann, F. A., Hill, N. J. The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics.* **63** (8), 1293-1313 (2001).

24. Wichmann, F. A., Hill, N. J. The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception & Psychophysics.* **63** (8), 1314-1329 (2001).

25. Zupan, L. H., Merfeld, D. M. Interaural self-motion linear velocity thresholds are shifted by roll vection. *Experimental Brain Research.* **191** (4), 505-511 (2008).

26. Carriot, J., Jamali, M., Cullen, K. E., Chacron, M. J. Envelope statistics of self-motion signals experienced by human subjects during everyday activities: Implications for vestibular processing. *PLoS ONE.* **12** (6), e0178664 (2017).

27. Agrawal, Y. et al. Decline in semicircular canal and otolith function with age. *Otology & Neurotology.* **33** (5), 832-839 (2012).

28. Rey, M. C. B. et al. Vestibular perceptual thresholds increase above the age of 40. *Frontiers in Neurology.* **7**, 162 (2016).

29. Lim, K., Karmali, F., Nicoucar, K., Merfeld, D. M. Perceptual precision of passive body tilt is consistent with statistically optimal cue integration. *Journal of Neurophysiology.* **117** (5), 2037-2052 (2017).

30. Agrawal, Y., Bremova, T., Kremmyda, O., Strupp, M. Semicircular canal, saccular and utricular function in patients with bilateral vestibulopathy: analysis based on etiology. *Journal of Neurology.* **260** (3), 876-883 (2013).

31. Bremova, T. et al. Comparison of linear motion perception thresholds in vestibular migraine and Menière's disease. *European Archives of Oto-Rhino-Laryngology.* **273** (10), 2931-2939 (2016).

32. King, S. et al. Self-motion perception is sensitized in vestibular migraine: pathophysiologic and clinical implications. *Scientific Reports.* **9** (1), 1-12 (2019).

33. Roditi, R. E., Crane, B. T. Directional asymmetries and age effects in human self-motion perception. *Journal of the Association for Research in Otolaryngology.* **13** (3), 381-401 (2012).

34. Kobel, M. J., Wagner, A. R., Merfeld, D. M. Impact of gravity on the perception of linear motion. *Journal of Neurophysiology.* **126** (3), 875-887 (2021).

35. Chow, M. R. et al. Posture, gait, quality of life, and hearing with a vestibular implant. *New England Journal of Medicine.* **384** (6), 521-532 (2021).