Artikel online veröffentlicht: 02.05.2023



# Interaction of Hearing and Balance

OPEN ACCESS

Authors
Ingmar Seiwerth

Affiliations
Department of Oto-Rhino-Laryngology, Head and Neck Surgery, University Hospital of Halle, Martin-Luther-University of Halle-Wittenberg, University Medicine of Halle (Saale), Germany

Key words
Audition, postural control, posturography, hearing rehabilitation, cochlear implant

Bibliography
Laryngo-Rhino-Otol 2023; 102: S35–S49
DOI 10.1055/a-1960-4641
ISSN 0935-8943

Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence
Dr. med. Ingmar Seiwerth
Department of Oto-Rhino-Laryngology, Head and Neck Surgery, University Hospital of Halle, Martin-Luther-University of Halle-Wittenberg, University Medicine of Halle
Ernst-Grube-Str. 40
06120 Halle (Saale)
Germany
ingmar.seiwerth@uk-halle.de

## ABSTRACT

There is increasingly assumed that, in addition to visual, vestibular and somatosensory afferents, hearing also plays a role in the regulation of balance. It seems that, especially in old age, progressive hearing loss is associated with a decrease in postural control. Several studies investigated this relationship in normal-hearing people, in patients with conventional hearing aids and with implantable hearing systems, as well as in patients with vestibular disorders. Despite the inhomogeneous study situation and lack of evidence, hearing seems to interact with the balance regulation system with potentially stabilizing effect. Furthermore, insights into audiovestibular interaction mechanisms could be achieved, which could possibly be integrated into therapeutic concepts of patients with vestibular disorders. However, further prospective controlled studies are necessary to bring this issue to an evidence-based level.

## Contents

## 1. Introduction

The regulation of balance is ensured by complex processing of afferent sensory information from the peripheral vestibular organs, the visual system, and the proprioceptive sensors [1]. While in healthy subjects the regulation of balance takes place largely in the background, its importance usually becomes apparent only when there is an inadequate or interrupted flow of information in one of the sensory systems, manifesting clinically as dizziness and vomiting, for example, in acute pathology of the peripheral vestibular system. Also in cases of loss of the visual axis, as it is the case in darkness, an increased risk of falling is found, being especially obvious in cases of additional damage of the other two pillars as for example in case of a pre-damaged peripheral vestibular organ or additional unevenness of the ground.

In recent years, the question has been increasingly investigated to what extent auditory information on the afferent side also contributes to balance regulation, and whether the auditory organ should even be considered as fourth pillar of postural regulation. The anatomical proximity as well as physiological interfaces may suggest an interaction between the auditory and vestibular organs. Nevertheless, this correlation has been little investigated so far, even though more and more research groups have been dealing with this question in recent years. Whether the influence of hearing on balance is more stabilizing or destabilizing and to what extent hearing plays a role in relation to the other sensory pillars in postural regulation cannot be answered in a blanket manner and requires a differentiated consideration of the respective situation, taking into account the complex sensory interaction mechanisms.

The aim of this paper is to provide an overview of this area with an explanation of the anatomical and physiological relationships taking into consideration the current state of studies. In addition, the correlation between hearing and balance will be examined in terms of clinical importance.

## 2. Anatomy and physiology

As components of the inner ear, the hearing system consisting of the cochlea and the vestibular system consisting of the utricle, saccule, and the three semicircular canals are anatomically closely connected, which also suggests a functional interaction (▶ **Fig. 1**). While auditory stimuli are processed into hearing impressions in the cochlea, the vestibular organ perceives changes in the position of the head in space in the form of rotational accelerations (semicircular canals) and linear accelerations (otolith organs; vertical: saccule; horizontal: utricle).

Evolutionarily, the otolith organs also worked as hearing organs; in addition to registering linear accelerations, the macula organs in fishes are also responsible for recording hearing impressions, which particularly involves saccule and lagena, a third macula organ found in fishes [2].

Even if the acoustic sensitivity of the macula organs is only rudimentary in humans and evolution has provided for a largely independent functioning of the auditory and vestibular organs despite the anatomical connection [3], it can still be used for diagnostic purposes: Stimulation of the otolith organs by sound, vibration, or galvanic stimuli may trigger a vestibular reflex that can be objectified by recording vestibular evoked myogenic potentials (VEMPs) [4]. In the case of suprathreshold stimulation with e. g. 500 Hz stimuli via air or bone conduction, potentials corresponding to the neuronal projections of saccule and utricle can be measured by means of electrodes at the contralateral eye muscles (oVEMPs, utricle) or the ipsilateral sternocleidomastoid muscle (cVEMPs, saccule) and the function of the macula organs can be assessed. Type I receptors are predominantly involved in the signal transmission of acoustic stimuli, while type II receptors are mainly responsible for encoding linear acceleration stimuli [2, 4, 5].

A relationship between cochlea and saccule may also play a role in degeneration processes: In a VEMPs-based study from 2012, Zuniga et al. [6] could show a significant correlation between both age-related and noise-induced hearing loss in the high frequency range and reduced saccule function in the form of reduced cVEMP amplitudes in patients older than 70 years. Interestingly, this relationship was not evident for utricle and semicircular canals. The authors suggest a possible explanation in embryology: The saccular part of the otic vesicle forms a tubular protrusion, the cochlear duct, in the 6$^{th}$ week, which develops into the cochlea, whereas the semicircular canals develop from the utricular part of the otic vesicle [7].

The anatomical connection between the vestibular organ and the cochlea can be illustrated especially in cases of pathologies, like for example the “third window syndrome”. If, as in the semicircular canal dehiscence syndrome [8–10], a defect in the bony labyrinth is found in addition to the oval and the round window, there is a “third window” through which sound energy can act on the semicircular system as well as escape. The noise-induced occurrence of vertigo is clinically known as Tullio phenomenon.

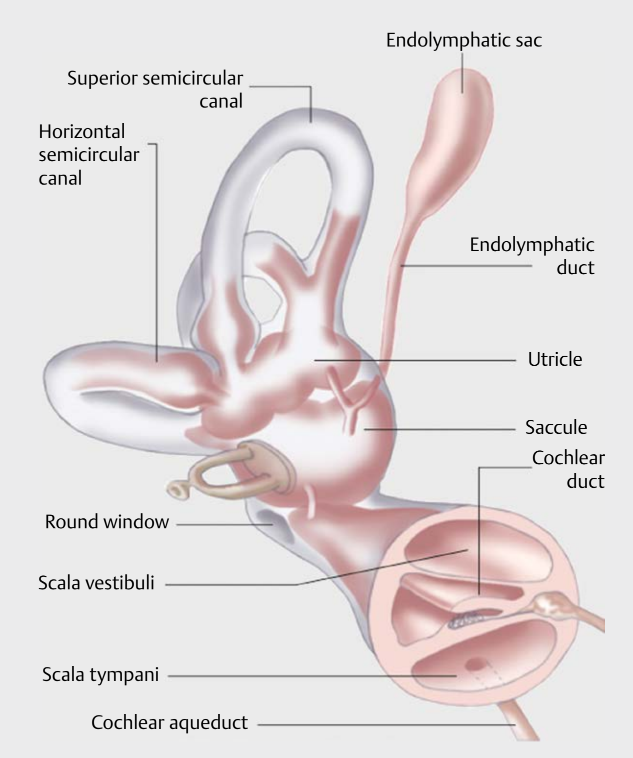
In the context of central neurology, the nigrostriatal and cerebellar systems in particular play a role in the postural regulation of balance on the efferent side [11]. In addition, linkages between vestibular and cochlear functions have been proven at several levels, which is described in detail in a paper by Anton et al. [12].

## 3. Correlation between hearing loss and balance

Epidemiological studies have increasingly shown a correlation between a reduction in hearing and a reduced balance function.

In a prospective observational study of elderly women, Viljanen et al. [13] described a correlation between hearing loss and impaired mobility. In another study, the same research group revealed an increased risk of falls with impaired hearing in elderly female twins [14]. Lin et al. [15] calculated an increase in the risk of falls by factor 1.4 for every 10 dB of hearing loss in hearing-impaired patients. A systematic review and meta-analysis by Jiam et al. [16] investigated the correlation between hearing loss and falls and concluded, based on 12 studies that met the inclusion criteria, that hearing loss is associated with a significantly increased risk of falls in elderly patients.

A prospective observational trial with 2190 participants performed by Chen et al. [17] revealed a correlation between reduced hearing and physical functional impairment over an observation period of 10 years. In addition, the authors described and increased risk of disability or need for long-term care associated with hearing loss for women of 31 % each. In a retrospective study including 1075 pati-




▶ **Fig. 1** Schematic representation of the membranous labyrinth (source: Strutz J, Mann W. Praxis der HNO-Heilkunde, Kopf- und Halschirurgie. Stuttgart: Thieme, 3. Auflage, 2017: 15).

ents, Berge et al. [18] showed that the decreasing hearing threshold was a strong predictor for an increased postural instability.

## 4. Hearing and balance in prospective trials

While epidemiological studies confirm a correlation between hearing and balance, questions remain, especially which (patho) physiological interaction mechanisms the audiovestibular interaction is based on.

Prospective cross-sectional or cohort studies allow the investigator to define influencing factors and endpoints according to targeted questions with the objective of obtaining a deeper understanding of the complex intersensory circuity as a basis for the long-term development of evidence-based therapeutic aspects.

In recent years, an increase in the relevance of this topic has been observed in the literature, which on one hand makes it easier to expand the overall knowledge of this area, but on the other hand creates ambiguity since the current study situation is characterized by inhomogeneity and lack of comparability [19–21].

### 4.1 Interaction of hearing and balance in normal-hearing subjects

#### 4.1.1 Stabilizing effect of auditory stimuli

The majority of studies investigating the interaction of hearing and balance in normal-hearing healthy subjects reported a rather positive impact of auditory input on balance.

**4.1.1.1 Quasi-static measurement procedures** With regard to the methods used to perform balance measurement, most of the papers published to date have applied quasi-static procedures like footplate measurement systems. The term “quasi”-static is deliberately used to distinguish from dynamic-mobile test procedures because slight movements are also involved during standing.

In a study conducted several years ago, Easton et al. [22] investigated body sway in 18 hearing-healthy subjects (10 of whom were blind from birth) with and without presentation of sound through two laterally or one frontally positioned loudspeaker. A reduction of body sway was described in the binaural lateral situation compared to the single frontal sound source, taking into account that there was a very short distance (5 cm) between the lateral loudspeakers and the auricle.

In a pilot study, Kanegaonkar et al. [23] addressed balance in the absence of sound. Postural stability was investigated in 20 young, healthy participants on a Nintendo Balance Board (Nintendo Company, Kyoto, Japan) in different test conditions. The authors were able to demonstrate, among other things, increased sway values when the examination took place in a sound-insulated room or with additional noise protection compared to a normal examination room.

In 19 normal-hearing participants, Zhong and Yost [24] investigated how spatial hearing (frontal sound source with white noise) affected the performance of the tandem Romberg test as well as the Fukuda (Unterberger) stepping test. A significant reduction of body sway under auditory stimulation was observed in both tests.

Ross et al. [25] described a reduction of the variability of body sway in 19 healthy subjects, which was measured by means of a footplate measurement system under exposure to white noise via headphones. This effect was confirmed in an older cohort by the same research group in a later study [26].

Vitkovic et al. [27] conducted an extensive trial in which postural sway on a Nintendo Wii balance board was investigated in normal-hearing subjects (n = 50), in patients with hearing loss (n = 28), and in patients with vestibular dysfunction (n = 19) under different auditory conditions. A positive effect on postural stability was described especially for rotatory stimuli.

In the studies performed by Gandemer et al. [28, 29], the focus was placed on the extent to which the nature of the auditory environment influences postural stability. Body sway was measured in healthy subjects (n = 20) using a footplate measurement system, while white noise was presented in a three-dimensional rotating field. In comparison, measurements were made without a sound source or with a stationary sound source, showing a reduction in body sway under rotational 3D input compared to control conditions [28]. In a subsequent paper, body sway was investigated in 35 healthy participants with different static sound sources in an anechoic and in a normal room. In another experiment, multiple three-dimensional soundscapes such as engine noise, cicada chirping, or bell ringing were added in an anechoic environment. The authors were able to demonstrate that the richer the auditory environment was to which the participants were exposed, the more pronounced was the reduction in body sway. The authors explained this observation using a model of an auditory spatial map, which is conceived at the cognitive level to orient the body in space [29].

In a study by Xu et al. [30], also based on a footplate measurement system, the authors addressed the question to what extent the frequency range as well as the loudness of music are relevant in the interaction with the vestibular system. For this purpose, postural stability was measured in 110 young subjects using a footplate measurement system under presentation of music with different frequency components (100 Hz, 1000 Hz, and 4000 Hz) and in two loudness groups (≥ 46.6 dB). This showed a benefit at 100 Hz and ≥46.6 dB, which was not the case in the other frequencies and at low sound levels. The authors consider this to be correlated to previous experimental studies [31, 32] in mice showing that an exposition of 100 Hz at 70 dB for one month resulted in vestibular damage, which, according to the authors, suggests a possible affinity of the vestibular organ for the low-frequency range.

Anton et al. [33] investigated the influence of different auditory stimuli on postural control in 30 healthy subjects. Upper body sway was measured in different standing conditions under five different acoustic conditions in two different rooms (short and long reverberation time). In summary, there was an increase in stability in an echo-rich room under presentation of interrupted auditory stimuli, while continuous noise caused a deterioration of postural stability.

Seiwerth et al. [34] investigated postural regulation and stability in 30 normal-hearing subjects under the conditions with and without auditory input. Noise (Fastl noise [35]) was presented in the free field over a frontal sound source. The measurement was performed using a footplate measurement system. This showed no change in postural stability. However, the system allowed a frequency-specific analysis of the postural subsystems, which revealed a reweighting with regard to their involvement in postural regulation (selective compensatory optimization model) under auditory input.

Ninomiya et al. [36] investigated the postural stability on a footplate measurement system in ten patients using hearing aids and ten normal-hearing subjects under frontal sound presentation. A reduction of swaying under presentation of auditory stimuli was found in the normal-hearing participants.

**4.1.1.2 Dynamic-mobile measurement methods** While most studies assessed postural stability using footplate measurement systems, some trials also investigated this issue using dynamic methods.

Munnings et al. [37] performed the Fukuda (Unterberger) stepping test with 44 normal-hearing and healthy subjects under different sensorimotor and auditory conditions and demonstrated a reduction in intrinsic rotation and longitudinal deviation when playing metronome sounds in a standard examination room.

Karim et al. [38] also revealed a reduction in angular deviation in eight young, healthy subjects when performing the Fukuda (Unterberger) stepping test under frontal presentation of white noise through a loudspeaker, which was not the case when sound was presented through headphones.

Seiwerth et al. [39] investigated vestibulopinal control using the Fukuda (Unterberger) stepping test under frontal presentation of noise (Fastl noise [35]) in 30 young, healthy subjects. They demonstrated a significant benefit under auditory input in terms of a reduction in longitudinal deviation and angle of rotation, while no difference was seen in angle of displacement.

Anton et al. [12] focused on the question of how auditory stimuli affect gait pattern. A sound source was presented to 30 healthy subjects in the room while they moved towards the sound source in different gait conditions. A reduction in upper body sway was demonstrated when walking with eyes open, with tandem steps, and when walking over obstacles, whereas there was no effect when walking with the head rotating.

### 4.1.2 No influence of auditory stimuli on balance

While the majority of studies that investigated the influence of hearing on balance reported a balance-stabilizing effect, there are also articles describing no influence or even a destabilizing effect of auditory stimuli on balance.

In the aforementioned paper by Easton et al. [22], no influence on postural stability was found under a different auditory condition with frontal spatial sound presentation.

In a study investigating the interaction of visual and auditory afferents with respect to postural stability in 23 healthy subjects, Palm et al. [40] could not demonstrate any influence of auditory stimuli (music through headphones) on postural stability compared to visual input.

Chen et al. [41] conducted a trial in 24 healthy subjects investigating the affective influence of auditory stimuli (unpleasant, neutral, or pleasant) on postural stability. The presentation was made through two loudspeakers in the room, while postural stability was evaluated on a footplate measurement system. There was no difference for both pleasant and neutral sounds, whereas there was a significant increase in sway in anterior-posterior direction for unpleasant sounds.

Azevedo et al. [42] assessed the postural stability on a footplate measurement system in 20 healthy subjects under different auditory conditions (without sound and without hearing protection, without sound and with hearing protection, with sound and without hearing protection, with sound and with hearing protection). No difference was found between the conditions.

Maheu et al. [43] also demonstrated no effect of white noise presented by posteriorly placed sound source on stability in different standing conditions in 14 healthy participants.

In a study investigating the effect of hearing on balance in cochlear implant (CI) patients on a footplate measurement system, Oikawa et al. [44] found no difference with or without sound presentation (white noise via a frontal loudspeaker) in the control group of eight healthy subjects with normal hearing.

Also in the already mentioned trial of Xu et al. [30] describing a stabilizing effect at 100 Hz, no influence was shown in higher frequencies (1000–4000 Hz).

Ibrahim et al. [45] measured postural stability using Romberg on foam and tandem standing test in 21 normal-hearing subjects and found no difference in stability under frontal sound presentation (3 kHz at 30 dB).

### 4.1.3 Destabilizing effect of auditory stimuli

However, a few studies also reported a destabilizing effect of auditory input on balance regulation in normal-hearing subjects.

 Seiwerth I. Interaction of Hearing and… Laryngo-Rhino-Otol 2023; 102: S35–S49 

Already in 1991, Raper and Soames [46] conducted a study with 30 young, healthy subjects who, standing on a footplate, were exposed to different auditory stimuli (silence, pure tone of 250 Hz, and background speech) in different spatial arrangements. In summary, an increase in sway was observed under auditory stimulation compared to the situation at silence, which led the authors to the conclusion of a destabilizing influence on balance.

Tanaka et al. [47] investigated the influence of white noise presented via headphones, which rotated from side to side, in twelve healthy subjects and found an increased sway using a footplate measurement system. After dividing the study population into a younger and an older group, this effect was even more pronounced in the group of elderly.

In another paper, also based on a footplate measurement system, Park et al. [48] observed an increased body sway with increasing frequency of sound presented via headphones in eleven healthy subjects.

In the study by Gago et al. [49], the condition was investigated in 24 hearing-healthy subjects with Alzheimer's disease and in 24 healthy participants, not by means of active presentation of auditory stimuli, but in the absence of ambient noise by wearing hearing protection. In the sound-suppressed situation, a reduction of body sway was revealed, which was measured by means of a footplate measurement system.

## 5. Interaction of hearing and balance in patients suffering from hearing loss

A stabilizing effect of hearing on balance leads to the assumption that, in addition to the primary intention of hearing improvement, device-based hearing rehabilitation can also play a role in improving postural stability and reducing the risk of falls. With this background, an increasing number of studies have been published in recent years, which have dealt with this topic predominantly in patients with hearing rehabilitation by means of hearing aids or CI. However, as it is the case for normal-hearing people, the studies are characterized by inhomogeneity with regard to study design, study population, and postural as well as auditory test conditions, which makes comparability and classification in the overall context considerably more difficult.

### 5.1 Influence of hearing rehabilitation by means of hearing aids on balance

In 2020, Borsetto et al. [19] were the first to publish a systematic review investigating the influence of hearing aids on balance control. For this review article, the authors were guided by the PRISMA criteria [50]. The search strategy yielded 5768 entries, of which eight papers (four cross-sectional studies, three controlled cross-sectional studies, and one non-randomized prospective trial) with a total of 200 patients met the criteria for inclusion in the systematic analysis.

Lacerda et al. [51] evaluated the influence of hearing aids in 56 elderly patients with bilateral sensorineural hearing loss and bilateral hearing aid fitting. The SF-36 questionnaire for the assessment of quality of life [52] and the FES-I questionnaire [53] for the evaluation of fear of falling were answered, and the Berg-Balance-Scale (BBS) [54] was performed as a balance test each before and four months after hearing aid fitting. An improvement of the quality of life as well as reduction of the fear of falling after hearing aid fitting could be revealed.

Rumalla et al. [55] analyzed the Romberg test on foam as well as the tandem standing test with punctual frontal presentation of white noise in the unaided and aided situation, i. e. with hearing aids on and off. In each case, the 14 patients who were 65 years of age and older showed a greater postural stability in the aided situation.

The previously mentioned study by Vitkovic et al. [27] was also included in the review of Borsetto et al. [19]. The group of hearing aid users (n = 28) showed no significant improvement of the stability in the aided situation. However, it could be observed that in the conditions with sound presentation, sway tended to increase in the unaided situation whereas there was a decrease in sway with hearing aids.

Negahban et al. [56] reported an improvement of postural stability with bilateral hearing aids. Increased sway on a footplate measurement system was observed in 22 hearing aid users in the unaided situation compared to the condition with hearing aids. In comparison to the patients with hearing aids, an unaided control group (n = 25) also showed increased sway. In each case, no noise was presented, and the measurements were made in a normal room.

Another trial that was included in the review was published by Shayman et al. [57]. The influence of hearing rehabilitation devices on gait was investigated in three patients with hearing loss. Two of them had hearing aids on both sides while one patient had bilateral CI. While walking on pressure sensors, step length and walking speed were measured, and the Mini-Balance Evaluation Systems Test (Mini-BEST [58]) was performed. The conditions were best-aided and unaided, respectively, and testing was performed in the presence of ambient noise generated by treadmills (gait analysis) or a nearby highway (Mini-BEST). All patients showed an improvement in gait speed in the best-aided situation.

Another study that did not investigate the static balance was published by Weaver et al. [59] who focused on the extent to which device-based hearing rehabilitation affected the gaid pattern. Gait analyses were performed in 13 patients with bilateral hearing aids and in 12 patients with bilateral CI while white noise superimposed by rain sounds was presented frontally. No difference was found between the aided and unaided auditory conditions in either group.

In the study by McDaniel et al. [60], that was also included, the Sensory Organization Test (SOT) consisting of six test conditions with and without hearing aids on a footplate measurement system was performed in 22 adult patients with bilateral hearing aids. Stereo multitalker babble was presented in the room. The authors could not show any improvement in postural stability between the two auditory conditions.

The research group of Maheu et al. [61] also investigated the influence of hearing on balance in 14 normal-hearing subjects and 18 patients with sensorineural hearing loss, ten of whom also had vestibulopathy. Postural stability was measured on a pressure measurement plate under different conditions (modified clinical test for sensory integration of balance, mCTSIB [62]). Pink noise was presented from posterior. It was shown that especially the group of hearing-impaired people with balance disorders had a benefit from hearing aids.

In another systematic review from 2021, which was also conducted using the PRISMA criteria, Ernst et al. [21] addressed the question if hearing rehabilitation by means of hearing aids or CI may lead to an improvement of balance disorders in higher ages or to a reduction of the risk of falls. After identification of 2598 articles, finally 10 studies were included in the qualitative analysis, five of which investigated the influence of hearing aids on balance, which had already been described in the review by Borsetto et al. [19]. These were the papers published by Lacerda et al. [51], Rumalla et al. [55] Negahban et al. [56], McDaniel et al. [60], and Weaver et al. [59]. The other papers included patients using CI, which will be discussed in a later section.

A review on this topic was published by Carpenter and Campos [20] that, however, was not performed according to PRISMA criteria, but applied relatively strict inclusion criteria. Only papers were considered that included at least one quantitative test with at least 30 s of standing on both legs in order to allow an objective comparison. The authors critically addressed the effect of hearing loss on balance. Among others, three studies with hearing aided patients were included, which have already been presented in the previous chapters (Negahban et al. [56] , Vitcovic et al. [27], and Maheu et al. [61]).

In their study, Ninomiya et al. [36] could show, as mentioned earlier, an improvement of sway for normal-hearing subjects that was observed in the anterior-posterior direction as well as in the medio-lateral direction. For the group of hearing aid users, however, this was the case only in the anterior-posterior direction.

In addition to normal-hearing subjects, Ibrahim et al. [45] analyzed nine patients with hearing aids and showed an improvement in the situation with hearing aids under sound presentation when performing both the Romberg test on foam and the tandem standing test, which was not the case for normal-hearing participants.

## 5.2 Influence of hearing rehabilitation by means of active middle ear and bone conduction implants on balance

A study by Seiwerth et al. [63] focused on the question of the interaction of hearing and balance in patients with active middle ear and bone conduction implants. Postural stability was assessed in 26 patients by means of static and dynamic measurement methods (Fukuda (Unterberger) stepping test, footplate measurement system, mobile posturography by means of trunk sway sensor) in each case in the best-aided and unaided situation with frontal presentation of noise (Fastl noise). Only the trunk sway in a mobile gait measurement showed a benefit from best fitting as well as isolated individual improvements in static posturography.

## 5.3 Influence of hearing rehabilitation by means of cochlear implants on balance

Compared to the situation in normal-hearing subjects or patients using hearing aids, the evaluation of audiovestibular interaction mechanisms is more complex in patients with CI.

A possible stabilizing benefit due to auditory stimuli must be weighed against a potential intervention-related vestibular impairment. Damage to vestibular structures by electrode insertion into the cochlea is possible already due to the anatomical conditions and has been investigated in several prospective and retrospective studies assessing the vestibular function before and after surgery. A meta-analysis published in 2017 by Ibrahim et al. [64] provides a detailed overview of this issue. Twenty-seven studies were included for analysis. A significant influence of CI surgery on the results of caloric testing as well as VEMP was found whereas no significant impact was seen on the results of the video head impulse test, on postural measurements, and on subjective evaluation of balance assessed by means of the DHI questionnaire (dizziness handicap inventory). However, the authors point out a strong heterogeneity of the results, which was due to relevant methodological differences and made a final evaluation difficult [64].

In analogy to the situation of patients with hearing aids, several studies have been conducted to investigate postural stability with and without CI.

The aforementioned review article by Carpenter and Campos [20] evaluated five trials that met the inclusion criteria.

Using a footplate measurement system, Suarez et al. [65] could not reveal any change in postural stability in the situations with and without CI in 13 children with unilateral CI.

Another research group led by Huang et al. [66] that investigated the vestibular function in children with CI, could not detect any difference in body sway on a footplate measurement system between the conditions of “CI on” and “CI off” in 24 unilaterally implanted participants.

Shayman et al. [67] investigated standing balance in 13 adults with bilateral (n = 10) and unilateral CI under the conditions of “CI on” and “CI off” using sensors placed at the body trunk and the head with frontal presentation of white noise. There was a significant reduction of acceleration as well as velocity of head movements in anterior-posterior direction with activated CI. In contrast, there was no significant effect on the body trunk with CI.

Oikawa et al. [44] investigated balance in normal-hearing subjects and eight patients with unilateral CI by means of a footplate measurement system with activated CI with and without presentation of white noise. In the absence of visual information without noise, a shift of the body center of gravity to the CI side was observed, which was not the case with sound presentation.

Miwa et al. [68] also used a footplate measurement system to assess the stability in nine patients with unilateral CI before intervention as well as >4 months postoperatively under the “CI on” and “CI off” conditions. A significant improvement of the stability with activated CI could be confirmed.

The systematic review by Ernst et al. [21] included a total of six studies with CI patients.

Weaver et al. [59] could not find any benefit with activated CI when examining the gait pattern of 12 patients.

Parietti-Winkler et al. [69] performed vestibular function diagnostics and postural stability testing by means of pressure plate measurement preoperatively and one year postoperatively in 10 patients with unilateral CI. They revealed an improvement in postural control one year after implantation, which was particularly evident in complex sensory test situations. In addition, the authors observed a compensation of vestibular deficits in the further course.

Louza et al. [70] calculated the risk of falls after CI implantation in 20 adult patients using mobile posturography with measurement times of one day preoperatively as well as three and five days after intervention and could not reveal any change in the risk of falls.

Guigou et al. [71] investigated in a prospective multicenter study 15 unilaterally implanted and seven bilaterally implanted patients with regard to postural stability using a footplate measurement system. In the sound-presenting condition, cocktail party sound was played in rotation via headphones, which resulted in a destabilizing effect in the bilaterally implanted group and a rather stabilizing effect in the unilaterally implanted group.

The study by Wiszomirka et al. [72] was also included. In this study, the postural stability was measured in 21 patients before and three months after cochlear implantation using a footplate measurement system, and no significant change in stability was observed. In addition, the previously described study by Oikawa et al. [44] was included in the review article.

Another study by Louza et al. [73] was not mentioned in the review articles. Here, the assessment of the risk of falls was performed in 33 patients with CI using a mobile measurement system focusing on different auditory situations (CI on/off, with music, with speech), and a slight but significant reduction of the risk of falls was observed, especially under presentation of music or speech.

Hallemans et al. [74], too, observed an improvement in gait under presentation of music in their pilot study of eight CI patients and bilateral caloric deficit.

The relationship between hearing and balance must be considered separately in CI patients. In addition to pure hearing improvement due to CI, there are other mechanisms to be taken into account: There is evidence that electrical co-stimulation of vestibular structures, in analogy to stimulation of the facial nerve [75], may occur by the CI. Several studies could confirm that CI stimulation can lead to stimulation of the otolith organs in the sense of recording e-cVEMPs [76–79] or e-oVEMPs [80]. One explanation would be the local spread of electrical stimulation to the vestibular structures [74, 81].

Regarding the interpretation of audiovestibular mechanisms in CI patients, apart from the inhomogeneous data situation, Borsetto et al. [19] see the following challenges: Adults are often unilaterally implanted with CI, which eliminates the stabilizing factor of binaural spatial hearing. Furthermore, the underlying disease causing the cochlear hearing loss may also be associated with a degeneration of vestibular inner ear structure. Ernst et al. [21] point out that neuroplasticity and adaptation to cochlear implantation, which takes a certain time, are of particular importance. Therefore, studies comparing for example conditions with "CI on" and "CI off" are considered critically, whereas longitudinal studies taking into account a sufficient time interval for neuroadaptation are considered as being much more significant.

## 6. Interaction of hearing and balance in patients with balance disorders

The majority of the studies conducted so far that dealt with the interaction of hearing and balance were performed on normal-hearing subjects or patients with device-related hearing rehabilitation. However, it seems to be reasonable to consider also the situation of patients with balance disorders. A few papers have specifically addressed this issue or included it in their study design.

Stevens et al. [82] used a center-of-gravity-based footplate measurement system to investigate the effect of auditory stimuli on balance in twelve patients without subjective vertigo and in eight patients with balance disorders of different etiologies. Testing was performed under various auditory, visual, and proprioceptive conditions. Among other things, white noise was presented spatially via four loudspeakers arranged crosswise. It was found that the more impaired balance was, the more the participants benefited from auditory input in terms of postural stability.

In the paper published by Vitkovic et al. [27] that has already been mentioned several times in this article, 19 patients with vestibular disorder were analyzed. It was particularly noticeable that these patients benefited to a greater extent from auditory stimuli, compared to patients and normal-hearing people without vestibular disorders. In the study by Shayman et al. [57], also cited above, the positive effect of hearing aid fitting was particularly evident in the patient with Menière's disease.

Also in Hallemans et al. [74], all eight cochlear implanted patients had bilateral vestibulopathy and could benefit from music with regard to their gait; and Maheu et al. [61] could also reveal a reduction of the risk of falls in patients with hearing impairment and concomitant vestibular pathology by hearing aids.

In contrast, the study by Wiszomirska et al. [72] did not demonstrate an auditory benefit on stability even in the group with vestibular disorders ($n = 10$).

In 2005, Dozza et al. [83] presented a method of auditory biofeedback in patients with bilateral vestibulopathy. Nine patients with bilateral vestibulopathy and a control group of nine healthy subjects underwent measurement of the postural stability by means of a footplate measurement system while auditory signals were presented via headphones as biofeedback. The information from the footplate that captured the sway was directly recoded into audiological signals that were forwarded to the patient, like for example an increase of the frequency or the volume corresponding to a certain direction of sway. Both groups showed improvement in stability with auditory biofeedback. Since the auditory signals finally provide coded cognitive information about the body position in space, which is no longer available to patients with vestibular loss, the focus of the mechanism of action is less on the purely acoustic character of the sound and more on the information content, in analogy to vibrotactile biofeedback systems [84].

## 7. Explanatory approaches for mechanisms of audiovestibular interaction

### 7.1 Auditory landmarks

Various models for mechanisms of audiovestibular interaction have been developed. One explanation for the stabilizing effect of auditory stimuli is that they represent spatial landmarks and can help to orient the body correctly in space [12, 19, 61]. A prerequisite for correct localization of the sound source is intact directional hearing, which is reported as a mean angular error between two and six degrees in normal-hearing subjects [85–87]. With this background, device-related hearing rehabilitation with a presumed improvement of directional hearing also plays a significant role.

Gandemer et al. [29] further developed the auditory landmark model into the theory of a spatial auditory map and concluded from their experiments with 3D sound presentation that the richer the auditory environment, the greater the stabilizing effect of spatial sound.

The selection of the examination room is also important. It is assumed that the reflections of sound sources, which can be external loudspeakers as well as the subject's own body sounds, are reflected from the walls of a normal examination room and can thus be used as additional auditory landmarks, which is not the case in anechoic rooms [23, 33].

### 7.2 Stochastic resonance

In experiments in which sound was transmitted via headphones, it may be assumed that the supporting effect of auditory signals as landmarks fails. This could also explain the results that no difference in postural stability could be found under sound presentation using headphones [38, 40]. Nevertheless, there are also experiments with headphones revealing a stabilizing effect on balance [25] so that audiovestibular interaction is possibly also based on other mechanisms.

Maheu et al. [43] introduced the possible explanation that was also taken up by Gandemer et al. [88], that auditory stimuli have a stabilizing effect on balance by means of stochastic resonance. The theory of cross-modal stochastic resonance describes that under auditory input, sensitivity is increased in other sensory components involved in balance control [89]. This increases, for example, the detection rate for primarily below-threshold visual and proprioceptive signals and integrates them into postural regulation [90, 91].

### 7.3 Reweighting of postural subsystems

Another hypothesis of audiovestibular interaction mechanisms describes that a failure or reduced function of one system involved in postural control may lead to an upregulation of another subsystem. This would explain why, in some studies, patients with balance disorders in particular may rely more on auditory stimuli as feedback.

The postural subsystems are involved differently in postural regulation depending on age, health status, and task. In the universal model of selective and compensatory optimization, Baltes and Baltes [92] describe the possibility that optimized functioning can be achieved by compensatory redistribution of resources. In the context of balance control, the principle of sensory redistribution mechanisms has already been presented by Asslander et al. [93].

Quantifying the hierarchical order of components involved in balance regulation appears rather difficult. In trials on hearing and balance, also experiments have been conducted in which sensory subsystems were suppressed in order to compare their involvement in postural control. In comparison to other sensory axes, like visual stimuli, hearing seems to play a minor role [22, 24, 49].

However, in balance regulation, not only the relative contribution of audiological stimuli seems to be important but also their possible property to induce a redistribution of postural resources. In this context, the above-mentioned explanation of stochastic resonance might play a role. The assumption that sensory redistribution mechanisms occur, is supported by studies of patients with vestibular disorders [27, 57, 82]. This group of patients is more likely to achieve a stabilizing effect of auditory input than subjects without vestibular disorder.

In their study, Maheu et al. [43] specifically investigated the redistribution mechanisms of postural sensory components under auditory input and described an increase in the weighting of the visual axis in the absence of auditory stimuli, which was not true for the proprioceptive axis. In Miwa et al. [68], a positive effect of CI was more evident when eyes were closed than with eyes open.

Seiwerth et al. [34] also investigated the aspect of sensory redistribution mechanisms. Normal-hearing patients showed reduced activity of the visual and vestibular axis under auditory input, whereas patients with hearing loss showed an upregulation of the vestibular axis in the best-aided situation [63].

### 7.4 Hearing loss and balance in higher ages

Results of epidemiological studies could show that hearing loss can also be associated with a reduced postural stability. Apart from a general reduction of neuronal and sensory capacities in higher ages, there are further explanations [20]: In addition to the aforementioned impaired binaural hearing with accompanying reduction of the ability to correctly orient the body in space, it has been revealed that impaired hearing needs more cognitive resources, which in turn may be lacking in necessary postural regulatory procedures and contribute to instability [94].

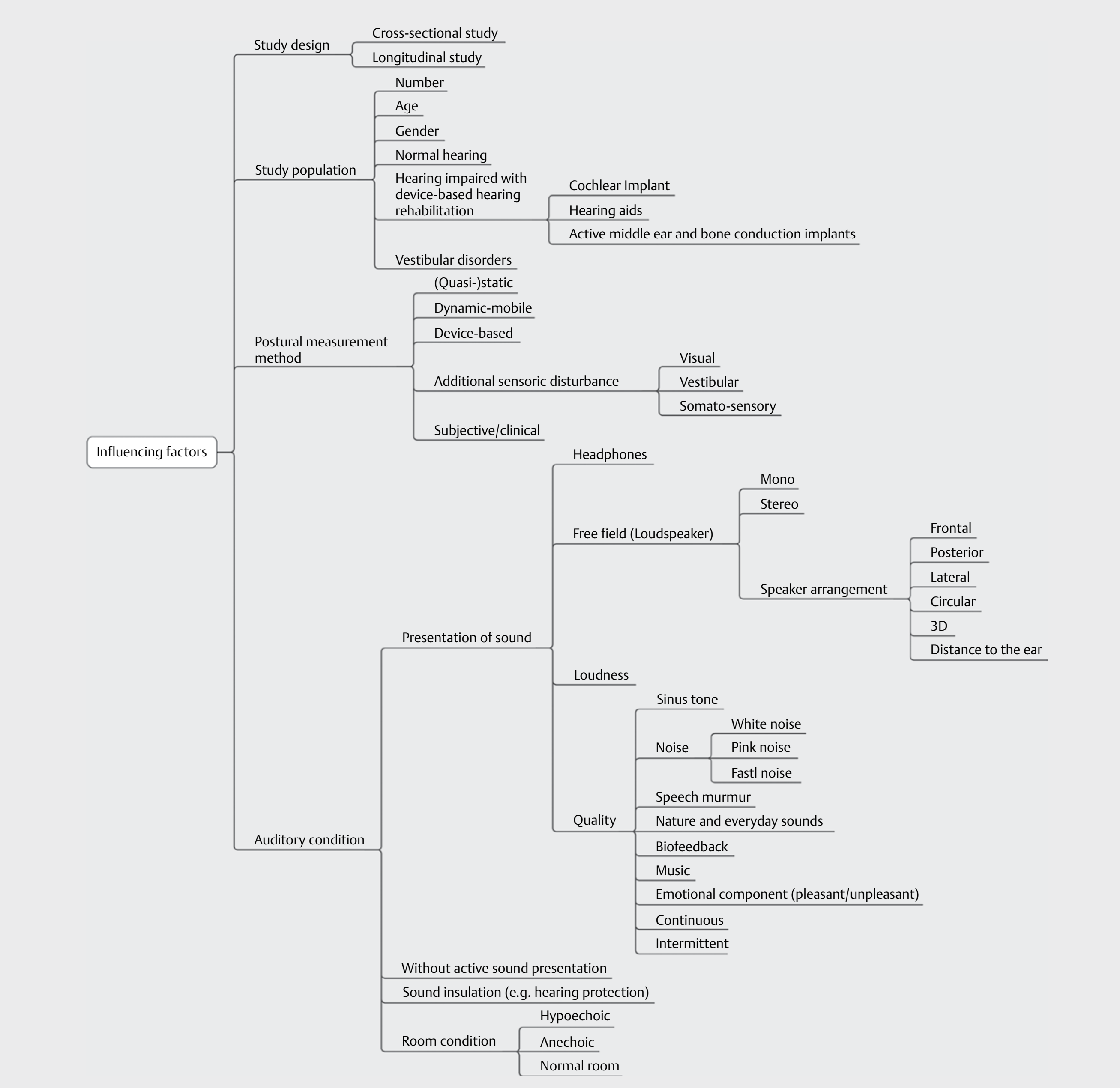
Finally, due to the anatomical similarities, the functional interconnection, and the embryonic relationship, it may be assumed that neuronal and structural degeneration processes of the cochlea and the vestibular organ follow pathophysiologically similar patterns [20].

## 8. Influencing factors in studies on hearing and balance

When reviewing the literature on hearing and balance, it is particularly noticeable that there is a great inhomogeneity with regard to multiple influencing factors, which makes comparability very difficult and a generalization of the results impossible [19–21]. This is also a possible explanation for the discrepancy of the results within the studies. The relevant influencing factors are explained and classified below (▶ **Fig. 2**).

### 8.1 Study design and study population

The majority of previous studies on hearing and balance are experimental cross-sectional studies in which different conditions are compared with each other in a study population within a test environment, like, for example, the conditions “best-aided” and “unaided” or “CI on” and “CI off” in intra-subject trials. As longitudinal studies, cohort studies such as the ones by Lacerda et al. [51] and Wiszomirska et al. [72] are an exception in this regard. As Ernst et al. [21] concluded, the long-term observation is more important because neuroplastic learning processes are taken into account when using auditory signals for balance control.

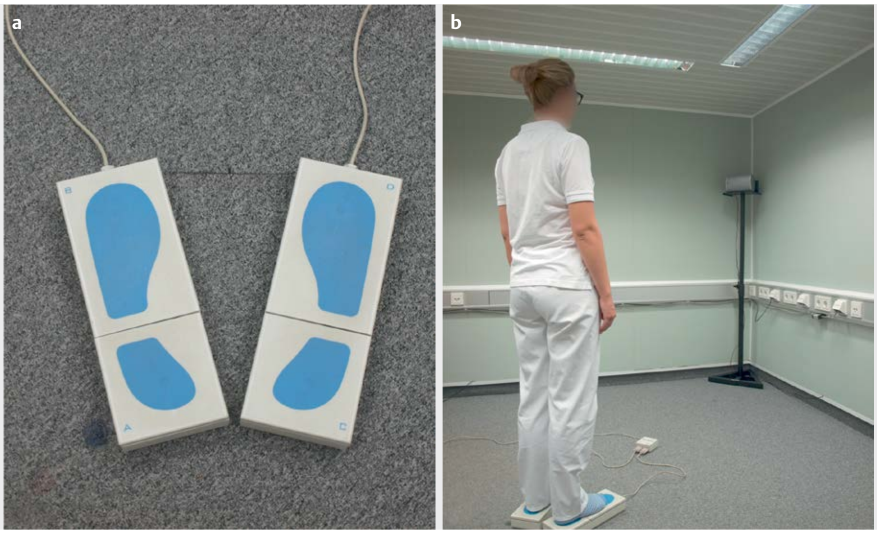



▶ **Fig. 2** Overview of relevant influencing factors in experimental studies on hearing and balance.

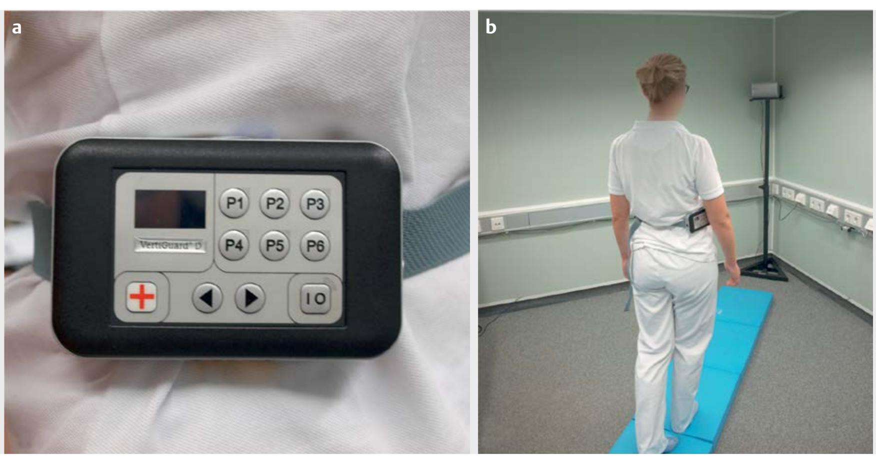
Regarding the study populations, a significant variability in terms of age, number, hearing and balance status as well as comorbidities of the study participants is particularly noticeable.

## 8.2 Measurement procedures for quantification of postural stability

A variety of methods and systems established in clinical practice are available for assessing postural control, and these play a major role as influencing factors in experiments on interaction with auditory signals. In addition to the subjective evaluation of balance by means of questionnaires [51], there are test procedures in which the examiner evaluates the performance of the test such as recording the duration of standing on one leg, the tandem standing test, or test batteries like the “timed up and go test”. However, these results are critical due to their subjective nature, which prompted Carpenter and Campos [20] to include only objective sway-based measurement procedures with a standing duration of > 30 seconds in their review.




► **Fig. 3** Example of a footplate measurement system. IBS (Interactive Balance System; neurodata GmbH Company, Vienna, Austria) that allows an analysis of postural subsystems in addition to force variations between forefoot heel by means of frequency-oriented Fast Fourier analysis of the force-time signal [104, 105]. a: footplates, arranged in 30° angle; b: application in measurements with frontal sound presentation in an anechoic room.




► **Fig. 4** Example for a trunk sway measurement system, Vertiguard (Zeisberg, Metzingen, Germany) which is attached at the hip near the center of gravity; a: assessment of trunk sway by means of acceleration sensors; b: application for dynamic-mobile measurement when walking on foam pads with frontal sound presentation in a hypoechoic room.

Many research groups conducted investigations on this issue using quasi-static measurement methods. Usually, the test person stands on a footplate measurement system that quantifies sways by means of pressure sensors and ensures objective evaluation (e.g. ► **Fig. 3**).

In contrast, it is possible to attach sensors to the body trunk (► **Fig. 4**) or systems with several sensors [59] or reflectors [74] to the trunk extremities and the head of the test person so that a differentiated analysis of the body sway is allowed and can be set in relation to the data of the extremities or the head. Gait analyses can also be assessed using pressure plates arranged as a track [57].

In addition to quasi-static tests, these measurement methods also enable mobile procedures like gait tests or test batteries such as SBDT and possibly come closer to clinical routine situations, such as in the evaluation of the risk of falls [95].

Furthermore, in all test procedures, disturbances or difficult conditions of the systems involved in postural regulation can be induced, such as the proprioceptive system by foam mats or the visual system by closed eyes.

## 8.3 Auditory environment

### 8.3.1 Sound presentation

The auditory setting plays a major role in experimental studies on the interaction of hearing and balance. In principle, it must be distinguished whether auditory stimuli are actively presented, whether only the ambient sounds of the examination room are used, or whether the measurement is performed in complete shielding of auditory signals (e. g. by wearing hearing protection).

Active sound presentation can be performed via headphones and in the free field by means of loudspeaker(s) in a wide variety of arrangements (mono, stereo, frontal, circular, three-dimensional), whereby the distance of the sound source to the ear and the loudness are also relevant factors.

In addition, the acoustic condition of the premises is of further importance. In a normal examination room, where sound waves are reflected by the walls, a certain reverberation time must be considered, while in a sound-proofed, low-echo, or anechoic room, no sound reflection is to be expected.

When evaluating studies or designing future trials, all this should be considered in the light of the possible explanation that auditory stimuli serve as spatial landmarks.

### 8.3.2 Sound quality

The quality of the sound presented also plays a crucial role.

In many articles, noise was used in different variations (often white noise, sometimes also pink noise or Fastl noise). However, experiments were also conducted with the presentation of sinus tones, murmurs, music, or everyday sounds. This is an important aspect, as it has also been shown that the emotional component evoked by a noise must not be neglected.

Chen et al. [41] revealed a decrease in postural stability with sounds that evoked unpleasant associations, such as "vomiting" or "screaming", and Anton et al. [33] also showed an increased upper body sway with continuous noise presentation compared to an improvement with intermittent noise.

In the article by Park et al. [48], already described above, the perceived annoyance of the noise was assessed according to frequency and loudness using a seven-point scale. A significant increase of the degree of subjective annoyance with increased frequency and loudness could be recognized. Whereas objectively no influence on stability was observed with regard to loudness, an increased sway in anteroposterior direction was shown with increasing frequency of the presented sound.

Also in the articles published by Seiwerth et al. with normal-hearing subjects [34, 39] and patients with hearing rehabilitation [96], the presented Fastl noise (a noise that resembles human speech with respect to its spectral distribution and envelope fluctuation) [35] was rather perceived as unpleasant.

In the case of music [73, 74], in addition to potentially individually pleasant (or also unpleasant) associations, the rhythmogenic effect is added during e. g. gait tests, whereby also a stabilizing effect can be achieved [73, 74].

The selection of sounds in experimental studies is in a sense a tightrope walk, since sound should serve as orienting support on one hand, but at the same time not be distracting. It is also assumed that balance may be impaired if subjects have to simultaneously perform cognitive tasks such as counting, arithmetic, etc. [97–103], as described in the review by Carpenter and Campos [20]. By occupying central neurological resources, there is competition with the connection of postural systems which may have a negative effect on cognitive testing as well as on postural measurements [20].

## 9. Conclusion and Outlook

Several epidemiological studies have clearly demonstrated a correlation between impaired hearing and reduced balance function, increased risk of falls, or impaired mobility.

Auditory stimuli appear to be involved in postural regulatory processes beside visual, proprioceptive, and vestibular information, albeit to a relatively much lesser extent than the respective visual, proprioceptive, or vestibular axis. The stabilizing effect seems to be higher when one of the other three axes (visual, vestibular, proprioceptive) is impaired or fails. The study situation also allows insights into the complex mechanisms of audiovestibular interaction and offers possible explanations with different models such as the auditory map or stochastic resonance. Auditory information can have both supporting and negative effects on postural control. Whether the effect on balance regulation is more stabilizing or more disturbing, seems to be related to the quality of the auditory stimuli.

However, it must be emphasized that the data situation is very inhomogeneous with regard to a large number of influencing factors, which significantly limits the comparability, significance and possibility of generalizing the respective results. In addition, the publication bias must be taken into account, which may lead to the assumption that there is a large number of unpublished, supposedly negative results.

Subject to the lack of evidence, it can be assumed, taking into account the studies published so far, that auditory information has the potential to interact with balance as well as to have a stabilizing effect on postural control under certain circumstances.

With this background, the following clinical aspects are relevant: The role of device-related and implantable hearing aids in the sense of pure function of auditory improvement is expanded to a support in balance regulation. In addition, when performing postural measurements in clinical routine, it should be kept in mind that ambient noise may influence the test result.

In the future, auditory signals could also play an important role in the development of rehabilitation therapies of vestibular disorders in terms of biofeedback systems or implemented virtual reality strategies.

Ultimately, however, controlled, prospective observational studies will be needed in the future to put questions investigating the correlation between hearing and balance on evidence-based, scientifically solid ground.

## 10. Acknowledgement

Special thanks go to Prof. René Schwesig for his critical review of the manuscript, as well as to Prof. Torsten Rahne, Prof. Stefan Plontke, Dr. Laura Fröhlich, and Dr. Alexandra Gey for their valuable suggestions and support in the preparation of this work.

### Conflict of interest

The author states that there is no conflict of interest.

## References


[1] Mergner T, Maurer C, Peterka RJ. Sensory contributions to the control of stance: a posture control model. Adv Exp Med Biol 2002; 508: 147–152

[2] Walther LE, Hormann K, Pfaar O. [Recording cervical and ocular vestibular evoked myogenic potentials: part 1: anatomy, physiology, methods and normal findings]. HNO 2010; 58: 1031–1045

[3] Carey J, Amin N. Evolutionary changes in the cochlea and labyrinth: Solving the problem of sound transmission to the balance organs of the inner ear. Anat Rec A Discov Mol Cell Evol Biol 2006; 288: 482–489

[4] Dlugaiczyk J. [Evidence-based diagnostic use of VEMPs : From neurophysiological principles to clinical application. German version]. HNO 2020; 68: 324–335

[5] Lue JH, Day AS, Cheng PW et al. Vestibular evoked myogenic potentials are heavily dependent on type I hair cell activity of the saccular macula in guinea pigs. Audiol Neurootol 2009; 14: 59–66

[6] Zuniga MG, Dinkes RE, Davalos-Bichara M et al. Association between hearing loss and saccular dysfunction in older individuals. Otol Neurotol 2012; 33: 1586–1592

[7] Sadler TW. Medizinische Embryologie. 10. Aufl. Stuttgart: Georg Thieme Verlag; 2003

[8] Minor LB, Solomon D, Zinreich JS et al. Sound- and/or pressure-induced vertigo due to bone dehiscence of the superior semicircular canal. Arch Otolaryngol Head Neck Surg 1998; 124: 249–258

[9] Rosowski JJ, Songer JE, Nakajima HH et al. Clinical, experimental, and theoretical investigations of the effect of superior semicircular canal dehiscence on hearing mechanisms. Otol Neurotol 2004; 25: 323–332

[10] Ward BK, Carey JP, Minor LB. Superior Canal Dehiscence Syndrome: Lessons from the First 20 Years. Front Neurol 2017; 8: 177

[11] Schwesig R, Becker S, Lauenroth A et al. [A novel posturographic method to differentiate sway patterns of patients with Parkinson's disease from patients with cerebellar ataxia]. Biomed Tech (Berl) 2009; 54: 347–356

[12] Anton K, Ernst A, Basta D. A static sound source can improve postural stability during walking. J Vestib Res 2021; 31: 143–149

[13] Viljanen A, Kaprio J, Pyykko I et al. Hearing acuity as a predictor of walking difficulties in older women. J Am Geriatr Soc 2009; 57: 2282–2286

[14] Viljanen A, Kaprio J, Pyykko I et al. Hearing as a predictor of falls and postural balance in older female twins. J Gerontol A Biol Sci Med Sci 2009; 64: 312–317

[15] Lin FR, Ferrucci L. Hearing loss and falls among older adults in the United States. Arch Intern Med 2012; 172: 369–371

[16] Jiam NT, Li C, Agrawal Y. Hearing loss and falls: A systematic review and meta-analysis. Laryngoscope 2016; 126: 2587–2596

[17] Chen DS, Betz J, Yaffe K et al. Association of hearing impairment with declines in physical functioning and the risk of disability in older adults. J Gerontol A Biol Sci Med Sci 2015; 70: 654–661

[18] Berge JE, Nordahl SHG, Aarstad HJ et al. Hearing as an Independent Predictor of Postural Balance in 1075 Patients Evaluated for Dizziness. Otolaryngol Head Neck Surg 2019; 161: 478–484

[19] Borsetto D, Corazzi V, Franchella S et al. The Influence of Hearing Aids on Balance Control: A Systematic Review. Audiol Neurootol 2021; 26: 209–217

[20] Carpenter MG, Campos JL. The Effects of Hearing Loss on Balance: A Critical Review. Ear Hear 2020; 41: Suppl 1 107S–119S

[21] Ernst A, Basta D, Mittmann P et al. Can hearing amplification improve presbyvestibulopathy and/or the risk-to-fall ? Eur Arch Otorhinolaryngol 2021; 278: 2689–2694

[22] Easton RD, Greene AJ, DiZio P et al. Auditory cues for orientation and postural control in sighted and congenitally blind people. Exp Brain Res 1998; 118: 541–550

[23] Kanegaonkar RG, Amin K, Clarke M. The contribution of hearing to normal balance. J Laryngol Otol 2012; 126: 984–988

[24] Zhong X, Yost WA. Relationship between postural stability and spatial hearing. J Am Acad Audiol 2013; 24: 782–788

[25] Ross JM, Balasubramaniam R. Auditory white noise reduces postural fluctuations even in the absence of vision. Exp Brain Res 2015; 233: 2357–2363

[26] Ross JM, Will OJ, McGann Z et al. Auditory white noise reduces age-related fluctuations in balance. Neurosci Lett 2016; 630: 216–221

[27] Vitkovic J, Le C, Lee SL et al. The Contribution of Hearing and Hearing Loss to Balance Control. Audiol Neurootol 2016; 21: 195–202

[28] Gandemer L, Parseihian G, Kronland-Martinet R et al. The influence of horizontally rotating sound on standing balance. Exp Brain Res 2014; 232: 3813–3820

[29] Gandemer L, Parseihian G, Kronland-Martinet R et al. Spatial Cues Provided by Sound Improve Postural Stabilization: Evidence of a Spatial Auditory Map? Front Neurosci 2017; 11: 357

[30] Xu H, Ohgami N, He T et al. Improvement of balance in young adults by a sound component at 100 Hz in music. Sci Rep 2018; 8: 16894

[31] Ohgami N, Oshino R, Ninomiya H et al. Risk Assessment of Neonatal Exposure to Low Frequency Noise Based on Balance in Mice. Front Behav Neurosci 2017; 11: 30

[32] Tamura H, Ohgami N, Yajima I et al. Chronic exposure to low frequency noise at moderate levels causes impaired balance in mice. PLoS One 2012; 7: e39807

[33] Anton K, Ernst A, Basta D. Auditory influence on postural control during stance tasks in different acoustic conditions. J Vestib Res 2019; 29: 287–294

[34] Seiwerth I, Jonen J, Rahne T et al. Postural regulation and stability with acoustic input in normal-hearing subjects. HNO 2020; 68: 100–105

[35] Fastl H. Ein Störgeräusch für Sprachaudiometrie. Audiol Acoustics 1987; 2: 22–13

[36] Ninomiya C, Hiraumi H, Yonemoto K et al. Effect of hearing aids on body balance function in non-reverberant condition: A posturographic study. PLoS One 2021; 16: e0258590

[37] Munnings A, Chisnall B, Oji S et al. Environmental factors that affect the Fukuda stepping test in normal participants. J Laryngol Otol 2015; 129: 450–453

[38] Karim AM, Rumalla K, King LA et al. The effect of spatial auditory landmarks on ambulation. Gait Posture 2018; 60: 171–174

[39] Seiwerth I, Jonen J, Rahne T et al. [Influence of hearing on vestibulospinal control in healthy subjects. German version]. HNO 2018; 66: 590–597

[40] Palm HG, Strobel J, Achatz G et al. The role and interaction of visual and auditory afferents in postural stability. Gait Posture 2009; 30: 328–333

[41] Chen X, Qu X. Influence of affective auditory stimuli on balance control during static stance. Ergonomics 2017; 60: 404–409

[42] Azevedo R, Teixeira N, Abade E et al. Effects of noise on postural stability when in the standing position. Work 2016; 54: 87–91

[43] Maheu M, Sharp A, Landry SP et al. Sensory reweighting after loss of auditory cues in healthy adults. Gait Posture 2017; 53: 151–154

[44] Oikawa K, Kobayashi Y, Hiraumi H et al. Body balance function of cochlear implant patients with and without sound conditions. Clin Neurophysiol 2018; 129: 2112–2117

[45] Ibrahim I, da Silva SD, Segal B et al. Postural stability: assessment of auditory input in normal hearing individuals and hearing aid users. Hearing Balanc Commu 2019; 17: 280–287

[46] Raper SA, Soames RW. The influence of stationary auditory fields on postural sway behaviour in man. Eur J Appl Physiol Occup Physiol 1991; 63: 363–367

[47] Tanaka T, Kojima S, Takeda H et al. The influence of moving auditory stimuli on standing balance in healthy young adults and the elderly. Ergonomics 2001; 44: 1403–1412

[48] Park SH, Lee K, Lockhart T et al. Effects of sound on postural stability during quiet standing. J Neuroeng Rehabil 2011; 8: 67

[49] Gago MF, Fernandes V, Ferreira J et al. Role of the Visual and Auditory Systems in Postural Stability in Alzheimer's Disease. J Alzheimers Dis 2015; 46: 441–449

[50] Moher D, Shamseer L, Clarke M et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 2015; 4: 1

[51] Lacerda CF, Silva LO, de Tavares Canto RS et al. Effects of hearing aids in the balance, quality of life and fear to fall in elderly people with sensorineural hearing loss. Int Arch Otorhinolaryngol 2012; 16: 156–162

[52] Ware JE Jr., Sherbourne CD. The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. Med Care 1992; 30: 473–483

[53] Yardley L, Beyer N, Hauer K et al. Development and initial validation of the Falls Efficacy Scale-International (FES-I). Age Ageing 2005; 34: 614–619

[54] Berg KO, Wood-Dauphinee SL, Williams JI et al. Measuring balance in the elderly: validation of an instrument. Can J Public Health 1992; 83: Suppl 2 S7–S11

[55] Rumalla K, Karim AM, Hullar TE. The effect of hearing aids on postural stability. Laryngoscope 2015; 125: 720–723

[56] Negahban H, Bavarsad Cheshmeh Ali M, Nassadj G. Effect of hearing aids on static balance function in elderly with hearing loss. Gait Posture 2017; 58: 126–129

[57] Shayman CS, Earhart GM, Hullar TE. Improvements in Gait With Hearing Aids and Cochlear Implants. Otol Neurotol 2017; 38: 484–486

[58] Franchignoni F, Horak F, Godi M et al. Using psychometric techniques to improve the Balance Evaluation Systems Test: the mini-BESTest. J Rehabil Med 2010; 42: 323–331

[59] Weaver TS, Shayman CS, Hullar TE. The Effect of Hearing Aids and Cochlear Implants on Balance During Gait. Otol Neurotol 2017; 38: 1327–1332

[60] McDaniel DM, Motts SD, Neeley RA. Effects of Bilateral Hearing Aid Use on Balance in Experienced Adult Hearing Aid Users. Am J Audiol 2018; 27: 121–125

[61] Maheu M, Behtani L, Nooristani M et al. Vestibular Function Modulates the Benefit of Hearing Aids in People With Hearing Loss During Static Postural Control. Ear Hear 2019; 40: 1418–1424

[62] Cohen H, Blatchly CA, Gombash LL. A study of the clinical test of sensory interaction and balance. Phys Ther 1993; 73: 346–351. discussion 351-344

[63] Seiwerth I, Brylok A, Schwesig R et al. Influence of Hearing Rehabilitation With Active Middle Ear and Bone Conduction Implants on Postural Control. Front Neurol 2022; 13: 846999

[64] Ibrahim I, da Silva SD, Segal B et al. Effect of cochlear implant surgery on vestibular function: meta-analysis study. J Otolaryngol Head Neck Surg 2017; 46: 44

[65] Suarez H, Angeli S, Suarez A et al. Balance sensory organization in children with profound hearing loss and cochlear implants. Int J Pediatr Otorhinolaryngol 2007; 71: 629–637

[66] Huang MW, Hsu CJ, Kuan CC et al. Static balance function in children with cochlear implants. Int J Pediatr Otorhinolaryngol 2011; 75: 700–703

[67] Shayman CS, Mancini M, Weaver TS et al. The contribution of cochlear implants to postural stability. Laryngoscope 2018; 128: 1676–1680

[68] Miwa T, Minoda R, Matsuyoshi H et al. The effect of cochlear implants on vestibular-evoked myogenic potential responses and postural stability. Auris Nasus Larynx 2019; 46: 50–57

[69] Parietti-Winkler C, Lion A, Montaut-Verient B et al. Effects of Unilateral Cochlear Implantation on Balance Control and Sensory Organization in Adult Patients with Profound Hearing Loss. Biomed Res Int 2015; 2015: 621845

[70] Louza J, Klappert CL, Ledderose G et al. Cochlear Implant Surgery and the Risk of Falls in an Adult Population. Otol Neurotol 2018; 39: e74–e79

[71] Guigou C, Toupet M, Delemps B et al. Effect of Rotating Auditory Scene on Postural Control in Normal Subjects, Patients With Bilateral Vestibulopathy, Unilateral, or Bilateral Cochlear Implants. Front Neurol 2018; 9: 972

[72] Wiszomirska I, Zdrodowska A, Tacikowska G et al. Does cochlear implantation influence postural stability in patients with hearing loss? Gait Posture 2019; 74: 40–44

[73] Louza J, Rosel C, Gurkov R et al. Influence of Cochlear Implantation on Postural Control and Risk of Falls. Audiol Neurootol 2019; 24: 245–252

[74] Hallemans A, Mertens G, Van de Heyning P et al. Playing Music May Improve the Gait Pattern in Patients with Bilateral Caloric Areflexia Wearing a Cochlear Implant: Results from a Pilot Study. Front Neurol 2017; 8: 404

[75] Cushing SL, Papsin BC, Gordon KA. Incidence and characteristics of facial nerve stimulation in children with cochlear implants. Laryngoscope 2006; 116: 1787–1791

[76] Basta D, Todt I, Goepel F et al. Loss of saccular function after cochlear implantation: the diagnostic impact of intracochlear electrically elicited vestibular evoked myogenic potentials. Audiol Neurootol 2008; 13: 187–192

[77] Coordes A, Basta D, Gotze R et al. Sound-induced vertigo after cochlear implantation. Otol Neurotol 2012; 33: 335–342

[78] Jin Y, Shinjo Y, Akamatsu Y et al. Vestibular evoked myogenic potentials evoked by multichannel cochlear implant – influence of C levels. Acta Otolaryngol 2008; 128: 284–290

[79] Rodriguez Montesdeoca I, Ramos de Miguel A, Gonzalez JCF et al. Differences in Vestibular-Evoked Myogenic Potential Responses by Using Cochlear Implant and Otolith Organ Direct Stimulation. Front Neurol 2021; 12: 663803

[80] Parkes WJ, Gnanasegaram JJ, Cushing SL et al. Vestibular evoked myogenic potential testing as an objective measure of vestibular stimulation with cochlear implants. Laryngoscope 2017; 127: E75–E81

[81] Hallemans A, Herssens N, Mertens G et al. Response to Weaver Ts, Shayman Cs, Huller Te. The Effect of Hearing Aids and Cochlear Implants on Balance during Gait. Otol Neurotol 2017;38: 1327-1332. Otol Neurotol 2018; 39: 518–519

[82] Stevens MN, Barbour DL, Gronski MP et al. Auditory contributions to maintaining balance. J Vestib Res 2016; 26: 433–438

[83] Dozza M, Chiari L, Horak FB. Audio-biofeedback improves balance in patients with bilateral vestibular loss. Arch Phys Med Rehabil 2005; 86: 1401–1403

[84] Basta D, Rossi-Izquierdo M, Soto-Varela A et al. Efficacy of a vibrotactile neurofeedback training in stance and gait conditions for the treatment of balance deficits: a double-blind, placebo-controlled multicenter study. Otol Neurotol 2011; 32: 1492–1499

[85] Akeroyd MA. An overview of the major phenomena of the localization of sound sources by normal-hearing, hearing-impaired, and aided listeners. Trends Hear 2014; 18:

[86] Dorman MF, Loiselle LH, Cook SJ et al. Sound Source Localization by Normal-Hearing Listeners, Hearing-Impaired Listeners and Cochlear Implant Listeners. Audiol Neurootol 2016; 21: 127–131

[87] Makous JC, Middlebrooks JC. Two-dimensional sound localization by human listeners. J Acoust Soc Am 1990; 87: 2188–2200

[88] Gandemer L, Parseihian G, Bourdin C et al. Sound and Posture: an Overview of Recent Findings. Computer Music and Multidisciplinary Reasearch (CMMR) 2016

[89] Lugo E, Doti R, Faubert J. Ubiquitous crossmodal Stochastic Resonance in humans: auditory noise facilitates tactile, visual and proprioceptive sensations. PLoS One 2008; 3: e2860

[90] Manjarrez E, Mendez I, Martinez L et al. Effects of auditory noise on the psychophysical detection of visual signals: cross-modal stochastic resonance. Neurosci Lett 2007; 415: 231–236

[91] Ohbayashi W, Kakigi R, Nakata H. Effects of white noise on event-related potentials in somatosensory Go/No-go paradigms. Neuroreport 2017; 28: 788–792

[92] Baltes PB, Baltes MM. Selective Optimization with Compensation – a Psychological Model of Successful Aging. Z Padagogik 1989; 35: 85–105

[93] Asslander L, Peterka RJ. Sensory reweighting dynamics in human postural control. J Neurophysiol 2014; 111: 1852–1864

[94] Pichora-Fuller MK, Kramer SE, Eckert MA et al. Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL). Ear Hear 2016; 37: Suppl 1 5S–27S

[95] Basta D, Rossi-Izquierdo M, Soto-Varela A et al. Mobile posturography: posturographic analysis of daily-life mobility. Otol Neurotol 2013; 34: 288–297

[96] Seiwerth I, Frohlich L, Schilde S et al. Clinical and functional results after implantation of the bonebridge, a semi-implantable, active transcutaneous bone conduction device, in children and adults. Eur Arch Otorhinolaryngol 2021. DOI:10.1007/s00405-021-06626-7

[97] Bernard-Demanze L, Dumitrescu M, Jimeno P et al. Age-related changes in posture control are differentially affected by postural and cognitive task complexity. Curr Aging Sci 2009; 2: 139–149

[98] Lajoie Y, Teasdale N, Bard C et al. Attentional demands for static and dynamic equilibrium. Exp Brain Res 1993; 97: 139–144

[99] Mahboobin A, Loughlin PJ, Redfern MS. A model-based approach to attention and sensory integration in postural control of older adults. Neurosci Lett 2007; 429: 147–151

[100] Maylor EA, Wing AM. Age differences in postural stability are increased by additional cognitive demands. J Gerontol B Psychol Sci Soc Sci 1996; 51: P143–P154

[101] Teasdale N, Bard C, LaRue J et al. On the cognitive penetrability of posture control. Exp Aging Res 1993; 19: 1–13

[102] Teasdale N, Simoneau M. Attentional demands for postural control: the effects of aging and sensory reintegration. Gait Posture 2001; 14: 203–210

[103] Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 2002; 16: 1–14

[104] Friedrich M, Grein HJ, Wicher C et al. Influence of pathologic and simulated visual dysfunctions on the postural system. Exp Brain Res 2008; 186: 305–314

[105] Schwesig R, Fischer D, Kluttig A. Are there changes in postural regulation across the lifespan? Somatosens Mot Res 2013; 30: 167–174