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Reference:

Peetermans Olivier, Dobbels Bieke, Mertens Griet, Moyaert Julie, van de Berg Raymond, Vanderveken Olivier M., Van de Heyning Paul, Fornos Angelica Perez, Guinand Nils, Lammers Marc, ...- Sound localization in patients with bilateral vestibulopathy
European archives of oto-rhino-laryngology / European Federation of Oto-Rhino-Laryngological Societies; European Laryngological Society - ISSN 1434-4726 - 279:12(2022), p. 5601-5613
Full text (Publisher's DOI): https://doi.org/10.1007/S00405-022-07414-7
To cite this reference: https://hdl.handle.net/10067/1883540151162165141

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Sound localization in patients with bilateral vestibulopathy

ABSTRACT

Purpose:
The goal of this study was to evaluate if bilaterally (partially) absent vestibular function during static sound localization testing, would have a negative impact on sound localization skills. Therefore, this study compared horizontal static sound localization skills of normal-hearing patients with bilateral vestibulopathy (BV) and healthy controls.

Methods:
Thirteen normal-hearing patients with BV and thirteen age-matched healthy controls were included. Sound localization skills were tested using seven loudspeakers in a frontal semicircle, ranging from -90° to +90°. Sound location accuracy was analyzed using the root-mean-square error (RMSE) and the mean absolute error (MAE). To evaluate the severity of the BV symptoms, the following questionnaires were used: Dizziness Handicap Inventory (DHI), Oscillopsia severity questionnaire (OSQ), 12-item Spatial, Speech, and Qualities Questionnaire (SSQ12), and Health Utilities Index Mark 3 (HUI3).

Results:
The RMSE and MAE were significantly larger (worse) in the BV group than in the healthy control group, with respective median RMSE of 4.6° and 0°, and a median MAE of 0.7° and 0°. The subjective reporting of speech perception, spatial hearing, and quality of life only demonstrated a moderate correlation between DHI (positive correlation) and HUI total score (negative correlation), and localization scores.

Conclusion:
Static sound localization skills of patients with BV were only mildly worse compared to healthy controls. However, this difference was very small and therefore most likely due to impaired cognitive function. The vestibular system does not seem to have a modulating role in sound localization during static conditions, and its impact is negligible in contrast to the impact of hearing impairment. Furthermore, the subjective reporting of speech perception, spatial hearing, and quality of life was not strongly correlated with localization scores.

Keywords
Bilateral Vestibulopathy, Sound Localization, Auditory Perception, Vestibular Function Tests, Hearing Loss

INTRODUCTION

The auditory (cochlea) and vestibular (endolymphatic duct, semicircular canals, utricle, saccule) components of the inner ear share a common embryologic origin, which is the otocyst or otic vesicle [1]. Due to the location in the inner ear, it was originally assumed that the semicircular canals were involved in sound localization. In 1824, Pierre Flourens made the first step in unraveling their true function, by surgically sectioning semicircular canals in pigeons [2]. After the procedure, all pigeons showed abnormal head movements and the inability to fly, but their hearing appeared to be spared. This discovery opened up further studies of the semicircular canals as functionally distinct from the cochlea. Nowadays, it is clear that the vestibular organs provide our central nervous system with information regarding the motion of the head as well as its orientation in the Earth's gravitational field, which is required for maintaining our balance and gaze stabilization. Recent findings have expanded the influence of the vestibular system to other functions such as spatial cognition, circadian rhythm, and several autonomic functions [3-5].

Bilateral partial or complete loss of vestibular function is a rare disease, known as bilateral vestibulopathy (BV) [6]. The bilateral impairment of vestibulo-ocular (VOR) and vestibulo-spinal reflexes in patients with BV mainly result in gait unsteadiness, postural imbalance, and blurred vision during head movements (i.e. oscillopsia). Due to the close anatomic relationship between inner ear vestibular and hearing structures, a large proportion of patients with BV are affected by sensorineural hearing loss [4]. Strong evidence exists that patients with BV suffer from impaired spatial cognition [3-5].

Unlike the retina, the cochlea is organized tonotopically, with position in the cochlea representing frequency instead of spatial location. The localization of sounds in the horizontal plane in humans, who have fixed external ears in contrast to most other mammals, is mainly based on interaural differences in time of arrival (ITD) and sound level (ILD), both of which require the use of binaural hearing. ITD and ILD cues are respectively used for localizing low-frequency and high-frequency sounds [7]. Secondary, monaural spectral cues (direction-dependent spectral filtering by the head and pinnae) are also used, allowing patients with unilateral deafness to perform horizontal sound localization to a lesser extent [8].

Although vision is the most important source of information, spatial representation is not limited by this. Auditory cues also play an important role as they cover a much wider field compared to the frontal field of visual cues. Unexpected sounds provoke reflexive fast head movements toward the sound source, allowing the stimulus to be visually encoded at a high resolution. A good sound localization ability is crucial for personal safety and facilitates speech understanding in noisy circumstances. Among blind humans, auditory space perception is all the more important and after several months of training, many of them are even capable of using echolocation through tongue clicks, similar to bats [9].

Due to their fixed external ears, humans are at a disadvantage compared to some animal species, as they are unable to use the vestibulo-auricular reflex, which consists of rapid compensatory pinnae movements in the opposite direction of head movements to optimize dynamic auditory space perception [10]. Nevertheless, humans perceive the auditory world to be stable despite constant body and head movements, due to the integration of vestibular, neck proprioceptive, and efference copy signals (i.e. the prediction of sensory consequences of one's own actions) regarding the motion of the head as well as its orientation in the Earth's gravitational field [11]. This process is known as multisensory integration and depends on different forms of sensory stimuli presented simultaneously, that are integrated depending on the reliability and importance of each stimulus [12]. The interaction between visual and auditory cues is well investigated, in contrast to the interaction between auditory and vestibular cues which is often neglected.

Vestibular cues from both the otoliths and semicircular canals may influence the perceived location of a fixed sound source. During rotational acceleration of the body, the perception of the auditory target will shift to the opposite direction of the self-rotation and will come back to the midline when a constant velocity is reached [13]. The reverse is true during deceleration. This phenomenon is called the "audiogyral illusion". In addition, rapid head turns can cause a compression of the auditory spatial perception, in analogy with visual saccades causing visual-spatial compression [14]. Such compression of the auditory scene was also observed during linear acceleration of the body, with a distortion of the sound image in the direction of movement during forward self-motion [15]. This phenomenon is called "audiographic illusion". Other studies have used a slow rotational room, demonstrating a shift of the sound image in the direction of the resultant linear gravito-inertial force [13, 16]. Furthermore, auditory perception is also influenced by changes in body position relative to gravity (body tilt) [17]. By creating different dynamic listening conditions, the above studies have demonstrated that localization accuracy is affected by vestibular stimulation. The question remains whether the vestibular system plays a role during static listening conditions since this has never been properly investigated. During these static conditions, vestibular cues are absent, except for the constant gravity vector which is sensed by the saccule. However, the vestibular system may have a modulating role in sound localization during static conditions. Therefore, patients with BV are a very interesting research group. Visual-spatial cognition is compromised in patients with BV, and the same may be true for auditory space perception.

To conclude this introduction, we hypothesized that the presence of a bilateral normal vestibular function during localization testing is also required to optimally localize a static sound source during static listening conditions. The goal of this study was to evaluate if bilaterally (partially) absent vestibular function during the localization test itself, will affect static sound localization skills. Therefore, this study compared horizontal sound localization skills of normal-hearing patients with BV and healthy controls, using a fixed sound source and during static listening conditions (primary outcome). Furthermore, this study investigated whether static sound localization skills of patients with BV were correlated with the subjective reporting of speech perception, spatial hearing, and quality of life (secondary outcome).

MATERIAL AND METHODS

Study design

A cross-sectional matched sample study was conducted at our ENT department, from September 2017 to March 2020.

Inclusion and exclusion criteria

All patients with BV were diagnosed at our department. All patients underwent vestibular, otological, neurological, MRI brain, and genetic examination. Patients with BV with clinical signs indicating cognitive or cerebellar impairment and other neurological diseases were excluded. The inclusion criteria were as follows:

- bilaterally reduced vestibular response in accordance with the BV Bárány Society guidelines [6], documented by:
    - caloric response: sum of bithermal maximum peak slow phase velocity on each side < 6°/s, and/or
    - rotatory chair test: horizontal angular vestibulo-ocular reflex gain < 0.1 upon sinusoidal stimulation, and/or
    - video-head impulse test (vHIT): bilaterally pathological horizontal angular vestibulo-ocular reflex gain < 0.6.
- unaided bilateral pure tone average (PTA) of 0.5, 1 and 2kHz ≤ 25 dB
- at least 18 years old

Furthermore, age-matched healthy subjects with normal hearing were included to establish normative data for the localization set-up. The following inclusion criteria were used: bilateral $PTA_{0.5,\ 1\ \text{and}\ 2kHz} \leq 25$ dB, and no history of otovestibular disorders which was questioned verbally. Older age is associated with worse sound localization skills, whereas gender has no impact [18]. Therefore, only age matching was applied at a range of ± 5 years.

Measurement

Sound localization

CCITT (Comité Consultatif International Téléphonique et Télégraphique) noise bursts of 1-second duration were presented and were roved by ± 5 dB (sound levels between 65 and 75 dB SPL). Sounds were digitally generated in MATLAB (The Mathworks 7.4). The sounds were delivered via broadband Fostex 6301 loudspeakers.

The protocol used in this experiment was reported previously by Mertens et al. [19]. Sound localization skills were investigated in an unaided condition in a sound-treated room. Seven loudspeakers located in a frontal semicircle in a horizontal plane at subject's head level were used (Figure 1). Each of the seven loudspeakers was assigned a number, which was visible to the participants (Figure 1). Speakers were 0.8 m from the listener's head and stimulus coordinates ranged from -90° to +90° in azimuth at intervals of 30°. Azimuth for loudspeaker k was represented by φ_k. In each trial, six stimuli were offered from each speaker in a random sequence, which makes a total of 42 stimuli. Sound localization referred to sound source identification.

This test was performed in both the patient group and in the healthy controls. No practice sessions were allowed, and the first attempt was recorded. To avoid bias from the head shadow effect, participants were not allowed to move their heads during stimulus presentations; this was enforced by the examiner. Subjects did not receive feedback about their performance during testing. For each of the 42 stimulus presentations, the participant had to indicate the perceived location of the sound source by saying the corresponding number of the loudspeaker. The judged azimuth in response to a loudspeaker k was recorded (ψ_k) and plotted on a confusion matrix. The X-axis represents the target loudspeaker φ_k and de Y-axis represents judged azimuth ψ_k.

Overall sound localization accuracy was analyzed using the root-mean-square error (RMSE) (equitation 1). Since RMSE distorts the localization accuracy by giving more weight to larger errors, the mean absolute error (MAE) was used as well (equitation 2). RMSE is calculated as the root-mean-square of the magnitudes of the differences between the azimuth angle of the sound presenting speaker (φ_k) and the azimuth angle of the judged speaker (ψ_k) across all 42 stimulus presentations. MAE is the absolute error in degrees, divided by the total amount of stimulus presentations (i.e. 42 stimuli).

$$(1)\ \mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{NM}}\sum_{\mathrm{k}=1}^{\mathrm{N}}\left(\psi_k - \varphi_k\right)^2}$$

$$(2)\ \mathrm{MAE} = \frac{1}{\mathrm{NM}}\sum_{\mathrm{k}=1}^{\mathrm{N}}\left|\psi_{\mathrm{k}} - \varphi_{\mathrm{k}}\right|$$

M is the number of stimuli per loudspeaker (= 42); N is the number of speakers (= 7).

Vestibular testing

Only the patients underwent vestibular testing to confirm the diagnosis of BV. All vestibular testing was performed by experienced examiners. Bilateral bithermal caloric irrigations were performed with water at 30°C and 44°C for 30 seconds. The examination was performed in a dark room with the patient in supine position with a head-incline of 30°. Nystagmus was recorded using electronystagmography. The parameter used for both ears was the maximum slow-phase velocity at the time of maximum response. Rotatory chair tests were performed in a dark room using sinusoidal rotation at 0.05 Hz with a peak velocity of 60°/s, using electronystagmography. The determined parameter was VOR gain. More detailed methodology and normative data have previously been described [20]. The vHIT was performed using the commercially available ICE impulse vHIT goggles (Natus ®, formerly known as Otometrics). These vHIT goggles have three incorporated gyroscopes to determine the angular head velocity and an infrared camera that records the velocity of the right eye. VOR gain was defined as the ratio of the area under the eye velocity curve to the head velocity curve from the impulse onset until the head velocity returned to zero again [21]. The horizontal, anterior, and posterior semicircular canals were examined, however, only VOR gain of the horizontal canals was included in this study. Horizontal impulses were performed with head velocities >200°/s. Mean VOR gain of ten impulses was used as final outcome parameter.

In addition, saccular function was evaluated by cVEMP testing. Details on the procedure have been published previously [22]. In short, a patient's saccular function was quantified by the response of the ipsilateral sternocleidomastoid muscle to air-conducted 500 Hz tone bursts presented monoaurally through insert phones. The test was performed with an auditory evoked potential system equipped with electromyographic software (Neuro-Audio, Difra, Belgium), with self-adhesive electrodes (Blue Sensor, Ambu, Denmark). The generated wave response included a typically biphasic shape, with two distinctive peaks (p13, n23). While decreasing the sound intensity of the tone bursts, the simulation threshold was evaluated. When such a p13n23 wave response was seen at 95 dB HL or lower, the cVEMP response was considered present, whereas the cVEMP response was considered absent when no p13n23 wave response was seen above 95 dB HL. Due to a technical error with the cVEMP device, no results could be obtained in four subjects with BV, 1 to 4 (Table 2).

Pure-tone Audiometry

Unaided pure-tone air-conduction thresholds (0.125 – 8 kHz) were determined using an Interacoustics AC40 Clinical audiometer in a sound-treated room. $\text{PTA}_{0.5,\ 1\text{ and }2\text{kHz}}$ (in dB HL) of both ears were calculated. Both the patients with BV and the healthy controls underwent hearing testing.

Patient-reported outcome measures

To evaluate the impact of BV on health-related quality of life, all patients with BV were sent the following questionnaires before the study visits. At the start of each test visit, all questionnaires were reviewed with the examiner and possible ambiguities were clarified.

Dizziness Handicap Inventory (DHI)

The DHI is a validated questionnaire to evaluate the effect of dizziness and loss of balance on quality of life [23]. This questionnaire consists of 25 items distributed over three subscales: emotional, functional, and physical aspects of daily life. For each item, patients had to choose between three answers: no (zero points), sometimes (two points), and yes (four points). The total score ranges from zero (no difficulty) to one hundred (highest difficulty), with higher DHI scores indicating a greater self-perceived handicap. Scores ranging from 16 to 24 points are considered a mild handicap, 36 to 52 points a moderate handicap, and > 54 points a severe handicap.

Oscillopsia severity questionnaire (OSQ)

This questionnaire evaluates the frequency of oscillopsia during everyday situations [24]. Patients had to rate nine situations, on a scale of zero (never oscillopsia in this situation) to five (always oscillopsia in this situation), with higher oscillopsia scores indicating a greater impact of oscillopsia on quality of life. In healthy US participants, scores range from 8.8 to 15.3 for ages 19 – 75 [25].

Short Version of the Spatial, Speech, and Qualities Questionnaire (SSQ12)

This twelve-item version of the SSQ was utilized to evaluate the self-perceived disability in daily life activities [26]. Patients had to rate twelve items, on a scale of zero (absolutely not) to ten (absolutely). The higher the SSQ scores, the greater the ability. The 6th (SSQ12/6), 7th (SSQ12/7), and 8th (SSQ12/8) questions of this questionnaire are specifically related to spatial hearing and will therefore be evaluated separately, in addition to the total SSQ12 score (Table 1). Normal values of the normal hearing US population include 8.8 for ages 18 – 22 and 7.7 for ages 64 – 80 [27].

SSQ12/6	You are outside. A dog barks loudly. Can you tell immediately where it is, without having to look?
SSQ12/7	Can you tell how far away a bus or a truck is, from the sound?
SSQ12/8	Can you tell from the sound whether a bus or truck is coming towards you or going away?

Table 1. The full 6th, 7th, and 8th questions of the SSQ12 questionnaire [26].

Health Utilities Index Mark 3 (HUI3)

This is a validated questionnaire to evaluate the health-related quality of life [28]. Eight specific domains are assessed: vision, hearing, speech, ambulation, agility, cognition, and pain, each on a scale with five or six response options. A total score ranging from one (perfect health) to zero (death) was obtained, with lower scores for poorer self-reported quality of life. The HUI3 is often used for economic cost-utility analysis. The HUI3-scores of the general US population are highly dependent on age, with reported mean scores of 0.854 for ages 18 – 44, 0.779 for ages 45 – 64, and 0.694 for ages over 65 [29].

Statistical analysis

Sample size estimations were calculated using G-Power software version 3.1.9.6 [30], using an alpha value of 0.05 and a beta value of 0.20 (power of 80%). Regarding RMSE, the primary outcome parameter, the one-tailed Mann-Whitney U test was selected. Based on the first results, the following input parameters were used: standard deviation (SD) healthy controls = 2, SD patients with BV = 6, mean effect healthy controls = 1, mean effect patients with BV = 6. This calculation yielded 24 individuals divided between both groups. Regarding the secondary outcome, the correlation bivariate normal model, two-tailed, was selected. Using a Spearman's rho correlation coefficient of 0.7 (strong positive correlation), a total sample size of at least 13 was required. Smaller correlation coefficients required a sample size larger than 13.

Data were collected in OpenClinica LLC (Waltham, MA, USA), an online database for electronic data registration and data management developed for clinical research, and SPSS Statistics Version 26.0 (IBM Corp. Armonk, NY) was used for the statistical analyses. Data concerning demographics, hearing status, and localization accuracy were summarized for both the patients with BV as the healthy controls, using descriptive statistics. Given the small sample size and non-normal distribution, quantitative data were presented as median and range (minimum and maximum). For the same reason, a non-parametric test (Mann-Whitney U test) was used to compare both groups for statistically significant differences (primary outcome). Within the BV group, localization accuracy was correlated with demographics (age, gender), hearing data (mean $\text{PTA}_{0.5,\ 1\ \text{and}\ 2\text{kHz}}$ left and right, difference $\text{PTA}_{0.5,\ 1\ \text{and}\ 2\text{kHz}}$ left and right), vestibular tests (caloric test, rotatory chair, vHIT, cVEMP) and questionnaires (SSQ12 and subquestions 6-8, HUI, DHI, OSQ), using Spearman's rho correlation coefficient (ρ) (secondary outcome). P-values below 0.05 were considered statistically significant.

RESULTS

Participants

Considering the in- and exclusion criteria, thirteen normal hearing patients with BV were included. A summary of the demographics, hearing results, presumed cause of BV, and vestibular test data of the included patients with BV can be found in Table 2.

Thirteen age-matched healthy subjects with normal hearing were included to establish normative data for the localization set-up. Age matching was applied at a range of ± 5 years. An overview of the healthy subjects' demographics and hearing data is presented in Online Resource 1.

The age and hearing status were nearly the same in both patients with BV and healthy controls, with respectively a mean age of 57.2 and 57.9 years and a mean $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ of 11.3 and 14.5 dB HL. Gender was not equally distributed, with a male:female ratio of 10:3 among the patients with BV and 5:8 among healthy controls.

As illustrated in Table 2 and Online Resource 1, nearly all patients and healthy controls had relatively symmetric hearing at all frequencies. The mean interaural $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ differences in patients with BV and healthy subjects were respectively 2.85 dB and 3.23 dB.

Localization

Five patients (38%) with BV made no errors, compared to twelve (92%) of the healthy controls. The RMSE and MAE were larger (i.e. worse) in the BV group than in the healthy controls (p-value = 0.014) (Figure 2). The median RMSE of patients with BV and healthy controls were respectively 4.6° (range 0 - 18.5°) and 0° (range 0 – 6.5°). The median MAE of patients with BV and healthy controls were respectively 0.7° (range 0 - 5.0°) and 0° (range 0 – 1.4°). The MAE and RMSE scores were not correlated with age, mean $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ of both ears, $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ difference between both ears, or gender. Furthermore, MAE and RMSE scores were not correlated with vestibular tests including mean vHIT gain of both ears, presence of a cVEMP response (unilateral absent response = 0.5, bilateral absent response = 0, or bilateral present response = 1), rotatory chair test gain or mean maximum slow-phase velocity at the time of maximum response of both ears. An overview of the individual confusion matrixes and localization scores of the patients with BV is shown in Figure 3.

Subject	Age at test moment (years)	Gender (F = female, M = male)	Presumed cause of BV	PTA $_{0.5,\ 1\ \text{and}\ 2\text{kHz}}$ right ear (dB HL)	PTA $_{0.5,\ 1\ \text{and}\ 2\text{kHz}}$ left ear (dB HL)	vHIT right (gain)	vHIT left (gain)	Caloric irrigation right: sum of bithermal max SPV (°/s)	Caloric irrigation left: sum of bithermal max SPV (°/s)	Rotatory chair test (gain)	cVEMP right (present or absent)	cVEMP left (present or absent)
1	55	M	Idiopathic	13	7	0.31	0.78	3	0	0.02	#	#
2	74	F	Idiopathic	25	22	1.01	0.74	3	4	0.1	#	#
3	65	M	Idiopathic	13	15	0.56	0.45	5	4	0.1	#	#
4	57	M	Idiopathic	7	13	0.44	0.45	0	0	0.09	#	#
5	60	M	Bilateral vestibular neuritis	7	10	0.2	0.25	0	0	0.11	present	present
6	29	M	Idiopathic	5	0	#	#	0	0	0.22	present	present
7	39	F	Idiopathic	3	0	0.82	0.88	0	0	0.04	absent	absent
8	72	M	Idiopathic	22	22	0.4	0.27	3	0	0.05	absent	absent
9	56	M	Idiopathic	10	13	0.09	0.41	0	0	0.02	absent	absent
10	49	M	Idiopathic	2	2	0.42	0.92	7	0	0.07	present	absent
11	72	M	Idiopathic	18	17	#	#	2	4	#	present	absent
12	68	F	Head trauma	25	20	0.73	0.63	0	3	#	absent	absent
13	47	M	Idiopathic	2	2	0.82	0.79	1	3	#	present	absent

Table 2. Overview of the demographics, hearing results, presumed cause of BV, and vestibular test data of the included patients with BV. #, missing data.

Patient-reported outcome measures

Except for 2 patients with BV who did not complete the OSQ, there were no missing data. The mean scores of the DHI, OSQ and HUI3 were respectively 28.2 (SD = 7.2), 20.9 (SD = 2.5) and 0.82 (SD = 0.06). The mean scores of SSQ12, SSQ12/6, SSQ12/7 and SSQ12/8 were respectively 7.5 (SD = 0.7), 8.3 (SD = 0.6), 8.3 (SD = 0.5) and 8.7 (SD = 0.5). An overview is presented in Table 3. There was a moderately positive correlation between the DHI and the RMSE/MAE scores ($\rho = 0.690$ for RMSE with $P < 0.01$ and $\rho = 0.660$ for MAE with $P < 0.05$) and a moderate negative correlation between the HUI total score and the MAE score ($\rho = -0.621$ with $P < 0.05$). There were no other statistically significant correlations between MAE/RMSE scores and other questionnaires.

Subject	DHI	OSQ	HUI3 total score	SSQ12 total score	SSQ12/6	SSQ12/7	SSQ12/8
1	52	23	0.46	9.1	9.0	8.0	10.0
2	56	#	1,00	7.6	10.0	9.0	10.0
3	14	9	0.97	9.3	10.0	10.0	10.0
4	42	11	0.91	4.4	10.0	10.0	10.0
5	14	17	0.92	7.2	7.5	7.5	7.5
6	28	22	0.54	7.3	10.0	9.0	9.0
7	16	21	0.97	9.1	5.0	8.0	8.0
8	48	#	0.63	5.3	10.0	8.0	10.0
9	28	27	0.72	6.8	7.0	7.0	8.0
10	16	27	0.97	9.8	10.0	10.0	10.0
11	6	11	0.97	10.0	10.0	10.0	10.0
12	86	36	0.65	3.0	5.0	5.0	5.0
13	8	26	0.97	6.6	8.0	7.0	8.0

Table 3. Overview of questionnaires data of patients with BV. #, missing data.

DISCUSSION

The goal of this study was to evaluate if bilaterally (partially) absent vestibular function during the localization test itself, would affect sound localization skills. Therefore, the primary objective was to compare horizontal sound localization skills of normal-hearing patients with BV and healthy controls, using a fixed sound source and during static listening conditions. Our study showed that normal-hearing patients with BV had worse static sound localization skills compared to healthy controls. However, the statistically significant difference between both groups was very small, especially compared to patients with unilateral deafness (mean MAE = 60°, mean RMSE = 80°), indicating that ITD and ILD cues are much more important than vestibular cues during static sound localization (Figure 4) [31].

Experiencing vertigo can effectively shift the sound localization image, as was demonstrated by Lewald et al. [32] using cold water irrigation during static listening conditions to stimulate one of the vestibular systems. Once BV is diagnosed, vertigo is an uncommon symptom, and as a result, the patients with BV in our study did not experience vertigo during sound localization testing. Patients with BV show a wide variety of often subtle symptoms, the most important ones being gait unsteadiness, postural imbalance, and oscillopsia. However, there was no obvious correlation between the subjective reporting of speech perception, spatial hearing, and quality of life on the one hand and the sound localization scores on the other hand. Therefore, the reduced sound localization scores in patients with BV could not be explained by induced sound image shifts as a consequence of asymmetric impairment of the vestibular organs.

Most patients with BV diagnosed at our department had some form of hearing loss. Hearing loss has been demonstrated to be an important independent risk factor for dementia and could therefore affect spatial hearing [33]. Furthermore, binaural hearing is essential to localize sounds in the horizontal plane. Therefore, patients with BV with hearing loss were excluded. Mild asymmetric hearing levels might also degrade spatial hearing, with a shift of the sound localization image to the better hearing ear. Just noticeable differences of ITD and ILD have been well investigated for different kinds of localization stimuli, sound frequencies, and localization angles. Previous studies showed that in optimal conditions, the threshold for ITD was 10 to 20 µsec and the threshold for ILD was 0.5 to 1 dB [7]. In our study, all included patients and healthy controls had more or less symmetric hearing at all frequencies. The mean interaural $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ difference in patients with BV was 2.85 dB, which was less compared to the healthy subjects (3.23 dB), and no correlation could be found between mean interaural $PTA_{0.5,\ 1\ \mathrm{and}\ 2kHz}$ difference and localization scores. Following a persistent mild asymmetric hearing loss, adaptation may be achieved either by learning a new relationship between the altered binaural cues and sound source location or by relying to a greater extent on monaural spectral cues [34, 35]. It is therefore unlikely that hearing status in our patient group had an adverse impact on their localization accuracy.

Several studies suggested a link between vestibular function and cognition [3-5]. Spatial cognition and navigation seemed to be significantly impaired in patients with BV [5, 36-39]. Moreover, recent studies showed evidence of a general cognitive decline [40, 41]. A systematic review by Dobbels et al. [4] pointed out that none of the studies investigating cognition in patients with BV corrected for hearing loss, meaning that the cognitive decline in patients with BV might be partially or completely caused by comorbid hearing loss. Therefore, Dobbels et al. [3] evaluated the cognition in patients with BV while correcting for hearing impairment, using a cognitive test battery specifically adapted to visually support oral instructions: the Repeatable Battery for the Assessment of Neuropsychological Status for Hearing Impaired Individuals (RBANS-H) [42]. The RBANS-H allowed evaluation of five different subscales of cognition, namely immediate memory/learning, visuospatial ability, language, attention, and delayed memory, which are summed to provide a total score. After correcting for hearing impairment, patients with BV scored significantly worse on the "attention" subscale. Attention deficit and cognitive impairment in patients with BV might have had a negative impact on the localization scores.

This study showed that patients with BV had mildly worse sound localization skills as was hypothesized. However, this difference was very small and therefore most unlikely due to bilaterally absent vestibular function, but rather as a consequence of the attention deficit and cognitive impairment. The duration of the existing BV would have been an interesting parameter to include, since BV patients with a longer disease duration might hypothetically have had a greater impact on their cognitive functions with consequently worse sound localization skills. However, patients were unable to provide an exact date of BV onset and therefore we decided to omit this parameter.

This study investigated auditory space perception in the horizontal plane during static listening conditions, using a static sound source. During these conditions, the only active vestibular vector was the gravity vector, which is sensed by the saccule. The cVEMP assesses the saccular function and its afferent pathways. No correlation could be found between cVEMP response and localization scores. However, correlations between vestibular test results and localization scores mean little since patients with BV have little to no residual vestibular function. These correlations would have been interesting if we had included the vestibular test results of the healthy subjects.

This is the second study to investigate sound localization skills of patients with BV. Recently, Dobbels et al. [43] performed the same sound localization test on 69 patients with BV under best-aided conditions (with hearing aids and/or cochlear implants) as they hypothesized a correlation between sound localization skills and frequency of falling. They had to reject this hypothesis as there was no significant difference between the RMSE of the fallers (mean RMSE 41.5° ± 29.8°) versus the non-fallers (mean RMSE 39.4° ± 33.5°). These localization scores were much worse compared to the scores in our study, since not only normal hearing patients with BV were included in the present study. Despite the best-aided conditions, hearing aids and/or cochlear implants were not able to provide normal binaural hearing. The impact of ITD and ILD cues on localization scores was therefore much greater than the impact of BV.

Interestingly, the relationship between vestibular function and sound localization goes both ways. Not only visual cues but also auditory cues can be used as spatial landmarks to improve postural stability [44, 45]. Furthermore, hearing aids in elderly patients seem to improve the stability during Romberg test and decrease the risk of falling [46].

The subjective reporting of speech perception, spatial hearing, and quality of life was measured with several questionnaires (SSQ12, DHI, OSQ, HUI3), of which only a moderate correlation could be demonstrated between DHI (positive correlation) and HUI total score (negative correlation), and localization scores (secondary objective). The DHI scores indicate that the handicap was perceived as severe by 2 patients with BV (15%) and as moderate by 3 (23%). Mean HUI3, DHI, and OSQ scores in our study are better, compared to the mean scores of patients with BV in other studies [4, 47, 48]. The better mean HUI3 score in our study can be explained by the fact that patients with BV in our study did not have comorbid hearing loss, whereas most patients with BV included in the other studies showed moderate to severe hearing loss which has a negative impact on quality of life. Hearing loss may also have a negative impact on postural stability as mentioned earlier and may therefore cause worse mean DHI scores. Furthermore, by only including normal hearing patients with BV, several common causes with hearing impairment that are associated with worse DHI scores due to recurrent vertigo attacks (such as some genetic etiologies and Meniere's disease) are excluded. No further conclusions can be drawn due to the small sample size.

Despite the small impairment of the static sound localization scores in patients with BV, there is an obvious self-perceived impact on sound localization during everyday life. Five (38%) of the patients with BV showed impaired SSQ12/6, SSQ12/7, and SSQ12/8 scores, which are the SSQ12 subscores specifically related to spatial hearing. However, these subscores represent mainly localization ability during dynamic listening conditions, in which an adequate vestibular function is probably more important. In healthy subjects, localization accuracy was affected by creating dynamic listening conditions [13-17]. In future research, it would be interesting to investigate similar localizations tests with dynamic listening conditions in patients with BV. In analogy with an impaired visual acuity during dynamic situations due to the impaired VOR in patients with BV, we hypothesize that sound localization accuracy of patients with BV will be worse compared to healthy subjects due to a larger shift of the sound localization image during head rotations. Finally, in 6 (46%) of the patients with BV, a significant impact on the total SSQ12 score could be demonstrated. This is partly due to the worse SSQ12/6, SSQ12/7, and SSQ12/8 scores. In addition, some patients with BV probably showed reduced speech comprehension due to limited presbycusis.

The small sample size was one of the biggest limitations of this study. BV is a rare condition with often subtle symptoms, leaving many patients undiagnosed. Patients with obvious symptoms such as severe hearing loss might seek medical attention faster. Therefore, most of the patients with BV diagnosed at our center showed some form of hearing loss. Secondly, this study only investigated horizontal sound source localization, using a fixed sound source and during static listening conditions, which is an egocentric task. However, this covered only a small part of auditory space perception. It would be interesting to expand this investigation to vertical and distance sound localization and allocentric tasks. The reality is a lot more complex with dynamic sound sources, which is difficult to create as shifts of sound sources are accompanied by the creation of unintentional sounds. Furthermore, it would be interesting to perform localizations tests with dynamic listening conditions in patients with BV, as mentioned earlier.

CONCLUSION

Most patients with BV had difficulties localizing sounds due to their hearing loss. Even those with preserved binaural hearing had worse horizontal sound localization skills, using a static sound source and during static listening conditions, compared to age-matched healthy controls. However, this difference was very small and therefore most likely due to impaired cognitive function. The vestibular system does not seem to have a modulating role in sound localization during static conditions, and its impact is negligible in contrast to the impact of hearing impairment. Furthermore, the subjective reporting of speech perception, spatial hearing, and quality of life was not strongly correlated with localization scores. Future studies should examine the auditory space perception of patients with BV during dynamic listening conditions, to evaluate if dynamic auditory acuity is diminished analogous to the reduced dynamic visual acuity in patients with BV.

REFERENCES

1. Driver EC, Kelley MW (2020) Development of the cochlea. Development 147:1-13. https://doi.org/10.1242/dev.162263
2. Flourens P (1842) Expériences sur les canaux semi-circulaires des oiseaux. In: Baillière JB (ed) Recherches Expérimentales Sur Les Propriétés Et Les Fonctions Du Système Nerveux Les Animaux Vertébrès. 2nd edn. Imprimerie de Bourgogne et Martinet, Paris. pp 454-468
3. Dobbels B, Mertens G, Gilles A et al (2019) Cognitive Function in Acquired Bilateral Vestibulopathy: A Cross-Sectional Study on Cognition, Hearing, and Vestibular Loss. Front Neurosci 13:340. https://doi.org/10.3389/fnins.2019.00340
4. Dobbels B, Peetermans O, Boon B et al (2019) Impact of Bilateral Vestibulopathy on Spatial and Nonspatial Cognition: A Systematic Review. Ear Hear 40:757-765. https://doi:10.1097/AUD.0000000000000679
5. Kremmyda O, Hufner K, Flanagin VL et al (2016) Beyond Dizziness: Virtual Navigation, Spatial Anxiety and Hippocampal Volume in Bilateral Vestibulopathy. Front Hum Neurosci 10:139. https://doi.org/10.3389/fnhum.2016.00139
6. Strupp M, Kim JS, Murofushi T et al (2017) Bilateral vestibulopathy: Diagnostic criteria Consensus document of the Classification Committee of the Barany Society. J Vestib Res 27:177-189. https://doi.org/10.3233/VES-170619
7. Mills AW (1958) On the Minimum Audible Angle. J Acoust Soc Am 30:237. https://doi.org/10.1121/1.1909553
8. Slattery WH 3rd, Middlebrooks JC (1994) Monaural sound localization: acute versus chronic unilateral impairment. Hear Res 75:38-46. https://doi.org/10.1016/0378-5955(94)90053-1
9. Nilsson ME, Schenkman BN (2016) Blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences. Hear Res 332:223-232. https://doi.org/10.1016/j.heares.2015.09.012
10. Tollin DJ, Ruhland JL, Yin TC (2009) The vestibulo-auricular reflex. J Neurophysiol 101:1258-1266. https://doi.org/10.1152/jn.90977.2008
11. Genzel D, Firzlaff U, Wiegrebe L et al (2016) Dependence of auditory spatial updating on vestibular, proprioceptive, and efference copy signals. J Neurophysiol 116:765-775. https://doi.org/10.1152/jn.00052.2016
12. Stein B, Stanford T (2008) Multisensory integration: current issues from the perspective of the single neuron. Nat Rev Neurosci 9:255–266. https://doi.org/10.1038/nrn2331
13. DiZio P, Held R, Lackner JR et al (2001) Gravitoinertial force magnitude and direction influence head-centric auditory localization. J Neurophysiol 85:2455-2460. https://doi.org/10.1152/jn.2001.85.6.2455
14. Leung J, Alais D, Carlile S (2008) Compression of auditory space during rapid head turns. Proc Natl Acad Sci U S A 105:6492-6497. https://doi.org/10.1073/pnas.0710837105
15. Teramoto W, Sakamoto S, Furune F et al (2012) Compression of auditory space during forward self-motion. PLoS One 7:e39402. https://doi.org/10.1371/journal.pone.0039402
16. Lackner JR, DiZio P (2010) Audiogravic and oculogravic illusions represent a unified spatial remapping. Exp Brain Res 202:513-518. https://doi.org/10.1007/s00221-009-2149-y
17. Lewald J, Karnath HO (2002) The effect of whole-body tilt on sound lateralization. Eur J Neurosci 16:761-166. https://doi.org/10.1046/j.1460-9568.2002.02117.x

18. Freigang C, Richter N, Rubsamen R et al (2015) Age-related changes in sound localisation ability. Cell Tissue Res 361:371-386. https://doi.org/10.1007/s00441-015-2230-8
19. Mertens G, Gilles A, Bouzegta R et al (2018) A Prospective Randomized Crossover Study in Single Sided Deafness on the New Non-Invasive Adhesive Bone Conduction Hearing System. Otol Neurotol 39:940-949. https://doi.org/10.1097/MAO.0000000000001892
20. Van Der Stappen A, Wuyts FL, Van De Heyning PH (2000) Computerized electronystagmography: normative data revisited. Acta Otolaryngol 120:724-730. https://doi.org/10.1080/000164800750000243
21. Macdougall HG, McGarvie LA, Halmagyi GM et al (2013) The video Head Impulse Test (vHIT) detects vertical semicircular canal dysfunction. PLoS One 8:e61488. https://doi.org/10.1371/journal.pone.0061488
22. Colebatch JG, Halmagyi GM, Skuse NF (1994) Myogenic potentials generated by a click-evoked vestibulocollic reflex. J Neurol Neurosurg Psychiatry 57:190-197. https://doi.org/10.1136/jnnp.57.2.190
23. Jacobson GP, Newman CW (1990) The development of the Dizziness Handicap Inventory. Arch Otolaryngol Head Neck Surg 116:424-427. https://doi.org/10.1001/archotol.1990.01870040046011
24. Guinand N, Pijnenburg M, Janssen M et al (2012) Visual acuity while walking and oscillopsia severity in healthy subjects and patients with unilateral and bilateral vestibular function loss. Arch Otolaryngol Head Neck Surg 138:301-306. https://doi.org/10.1001/archoto.2012.4
25. Anson ER, Gimmon Y, Kiemel T et al (2018) A Tool to Quantify the Functional Impact of Oscillopsia. Front Neurol 9:142. https://doi.org/10.3389/fneur.2018.00142
26. Noble W, Jensen NS, Naylor G et al (2013) A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: the SSQ12. Int J Audiol 52:409-412. https://doi.org/10.3109/14992027.2013.781278
27. Banh JG, Singh G, Pichora-Fuller MK (2012) Age affects responses on the Speech, Spatial, and Qualities of Hearing Scale (SSQ) by adults with minimal audiometric loss. J Am Acad Audiol 23:81-91. https://doi.org/10.3766/jaaa.23.2.2
28. Horsman J, Furlong W, Feeny D et al (2003) The Health Utilities Index (HUI): concepts, measurement properties and applications. Health Qual Life Outcomes 1:54. https://doi.org/10.1186/1477-7525-1-54
29. Luo N, Johnson JA, Shaw JW et al (2005) Self-reported health status of the general adult U.S. population as assessed by the EQ-5D and Health Utilities Index. Med Care 43:1078-1086. https://doi.org/10.1097/01.mlr.0000182493.57090.c1
30. Faul F, Erdfelder E, Buchner A et al (2009) Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behavior Research Methods 41:1149-1160. https://doi.org/10.3758/BRM.41.4.1149
31. Mertens G, Desmet J, De Bodt M et al (2016) Prospective case-controlled sound localisation study after cochlear implantation in adults with single-sided deafness and ipsilateral tinnitus. Clin Otolaryngol 41:511-518. https://doi.org/10.1111/coa.12555
32. Lewald J, Karnath HO (2000) Vestibular influence on human auditory space perception. J Neurophysiol 84:1107-1111. https://doi.org/10.1046/j.1460-9568.2002.02117.x
33. Livingston G, Sommerlad A, Orgeta V et al (2017) Dementia prevention, intervention, and care. Lancet 390:2673-2734. https://doi.org/10.1016/S0140-6736(17)31363-6
34. Keating P, King AJ (2013) Developmental plasticity of spatial hearing following asymmetric hearing loss: context-dependent cue integration and its clinical implications. Front Syst Neurosci 7:123. https://doi.org/10.3389/fnsys.2013.00123

35. Kumpik DP, King AJ (2019) A review of the effects of unilateral hearing loss on spatial hearing. Hear Res 372:17-28. https://doi.org/10.1016/j.heares.2018.08.003
36. Brandt T, Schautzer F, Hamilton DA et al (2005) Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans. Brain. 128:2732-2741. https://doi.org/10.1093/brain/awh617
37. Glasauer S, Amorim MA, Viaud-Delmon I et al (2002) Differential effects of labyrinthine dysfunction on distance and direction during blindfolded walking of a triangular path. Exp Brain Res. 145:489-497. https://doi.org/10.1007/s00221-002-1146-1
38. Glasauer S, Amorim MA, Vitte E et al (1994) Goal-directed linear locomotion in normal and labyrinthine-defective subjects. Exp Brain Res 98:323-335. https://doi.org/10.1007/BF00228420
39. Grabherr L, Cuffel C, Guyot JP et al (2011) Mental transformation abilities in patients with unilateral and bilateral vestibular loss. Exp Brain Res 209:205-214. https://doi.org/10.1007/s00221-011-2535-0
40. Bessot N, Denise P, Toupet M et al (2012) Interference between walking and a cognitive task is increased in patients with bilateral vestibular loss. Gait Posture 36:319-321. https://doi.org/10.1016/j.gaitpost.2012.02.021
41. Popp P, Wulff M, Finke K et al (2017) Cognitive deficits in patients with a chronic vestibular failure. J Neurol 264:554-563. https://doi.org/10.1007/s00415-016-8386-7
42. Claes AJ, Mertens G, Gilles A et al (2016) The Repeatable Battery for the Assessment of Neuropsychological Status for Hearing Impaired Individuals (RBANS-H) before and after Cochlear Implantation: A Protocol for a Prospective, Longitudinal Cohort Study. Front Neurosci 10:512. https://doi.org/10.3389/fnins.2016.00512
43. Dobbels B, Lucieer F, Mertens G et al (2020) Prospective cohort study on the predictors of fall risk in 119 patients with bilateral vestibulopathy. PLoS One 15:e0228768. https://doi.org/10.1371/journal.pone.0228768
44. Hallemans A, Mertens G, Van de Heyning P et al (2017) Playing Music May Improve the Gait Pattern in Patients with Bilateral Caloric Areflexia Wearing a Cochlear Implant: Results from a Pilot Study. Front Neurol 8:404. https://doi.org/10.3389/fneur.2017.00404
45. Zhong X, Yost WA (2013) Relationship between postural stability and spatial hearing. J Am Acad Audiol 24:782-788. https://doi.org/10.3766/jaaa.24.9.3
46. Rumalla K, Karim AM, Hullar TE (2015) The effect of hearing aids on postural stability. Laryngoscope 125:720-723. https://doi.org/10.1002/lary.24974
47. Lucieer FMP, Van Hecke R, van Stiphout L et al (2020) Bilateral vestibulopathy: beyond imbalance and oscillopsia. J Neurol 267:241-255. https://doi.org/10.1007/s00415-020-10243-5
48. Guinand N, Boselie F, Guyot JP et al (2012) Quality of life of patients with bilateral vestibulopathy. Ann Otol Rhinol Laryngol. 121:471-477. https://doi.org/10.1177/000348941212100708

Figure 1

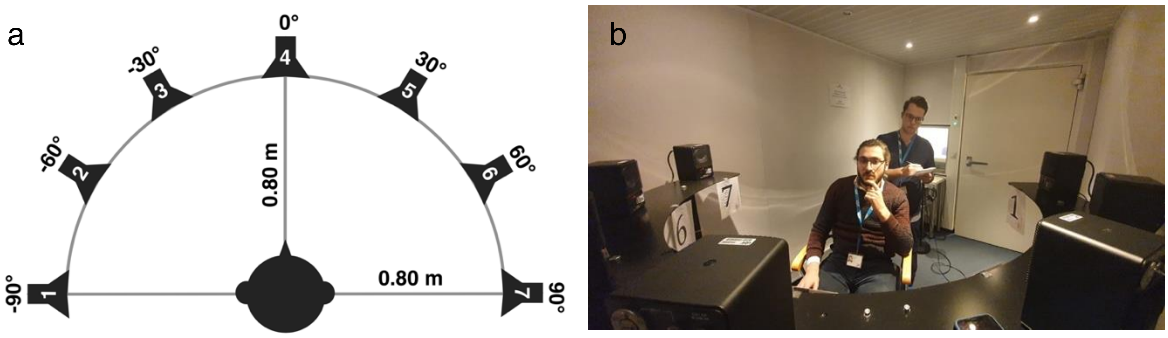


Fig. 1 Localization set-up: 7 Broadband Fostex 6301 loudspeakers at intervals of 30°, located in a frontal horizontal semicircle at the subject's head level. (a) Schematic representation and (b) picture of set-up.

Graphics program used: PowerPoint (Microsoft)

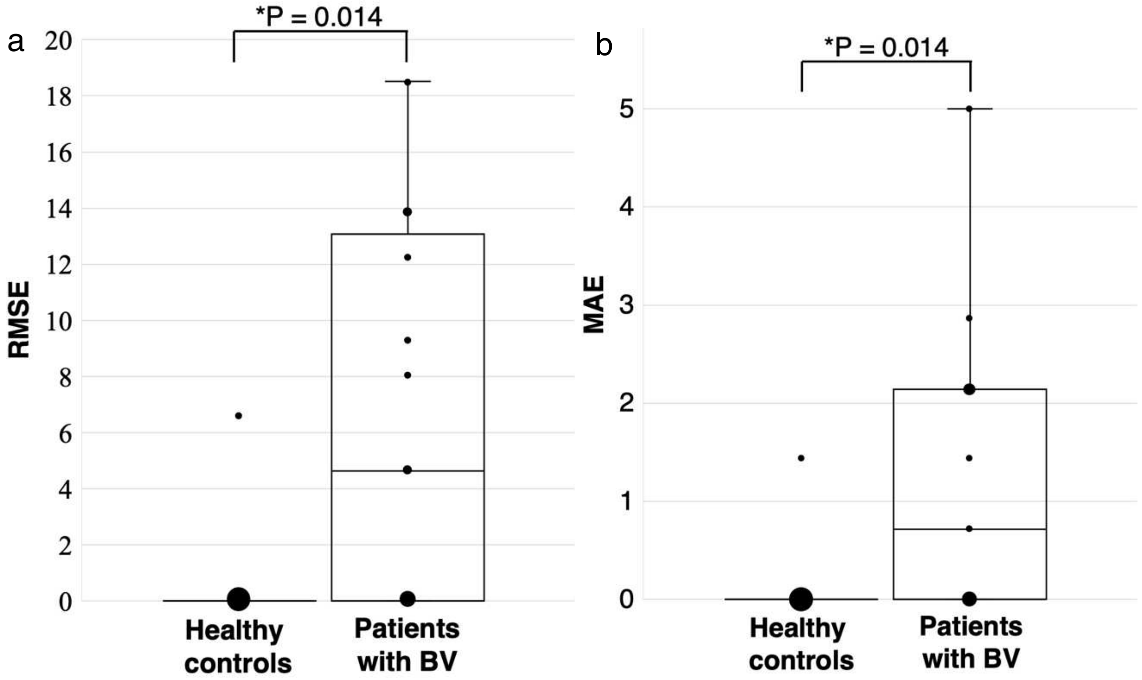


Fig. 2 Localization parameters of both the patients with BV and the healthy controls. (a) represents the root-mean-square error (RMSE) and (b) the mean absolute error (MAE). Significant differences between both groups are indicated by an asterisk, including accompanied p-values.

Graphics program used: IBM SPSS Statistics (version 27) and edited in PowerPoint (Microsoft)

Figure 3

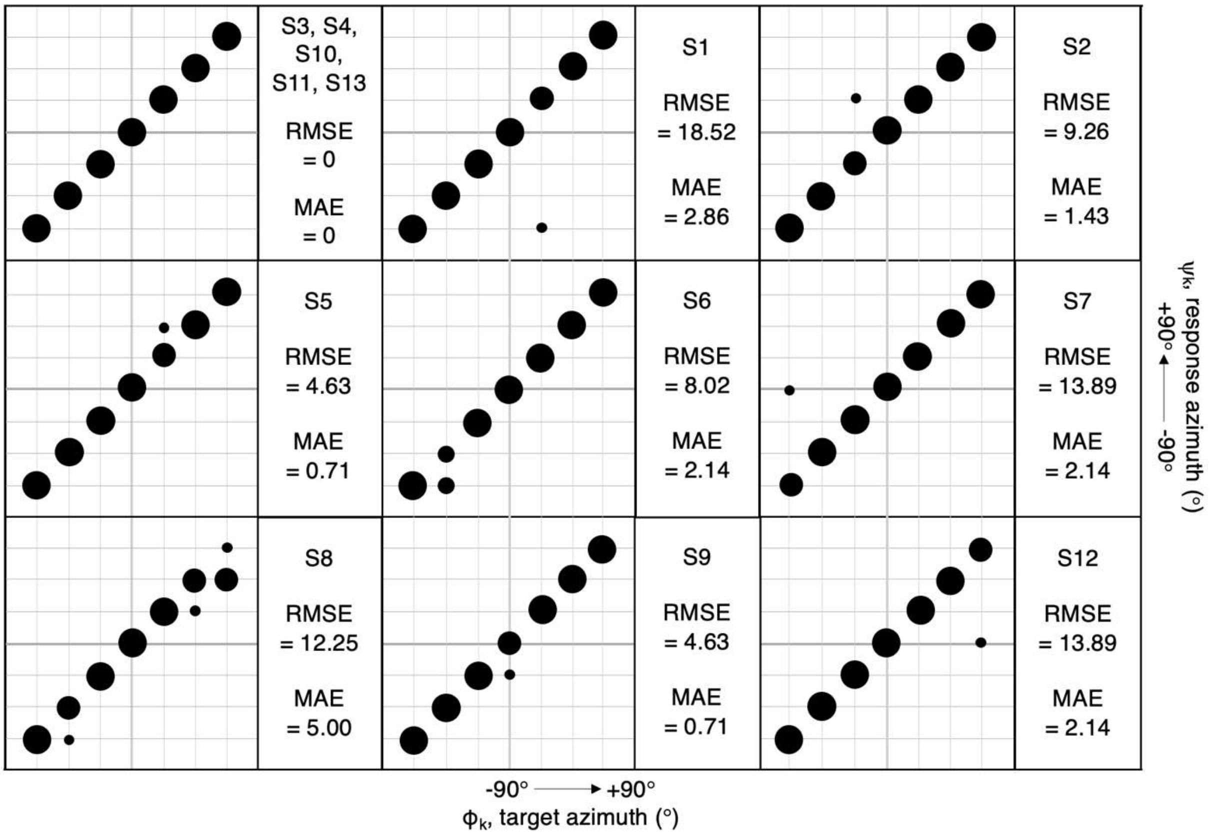
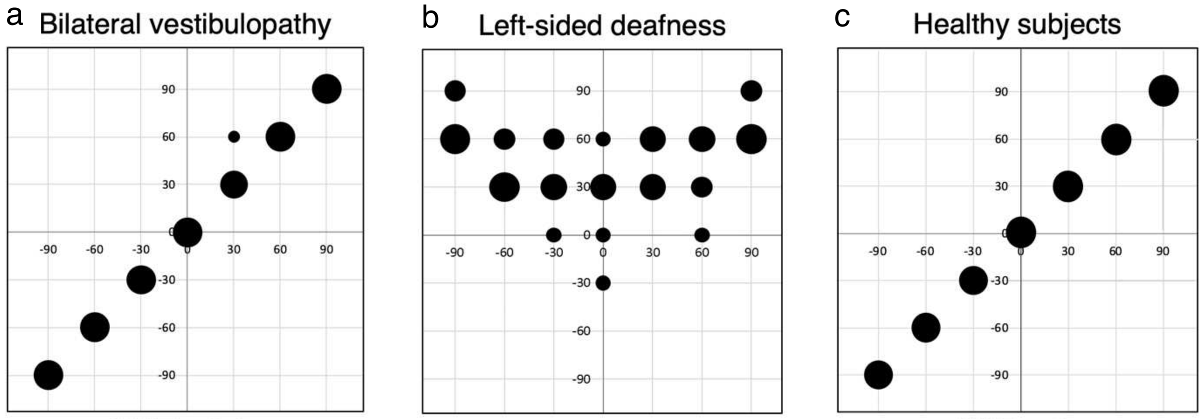


Fig. **3** An overview of the individual confusion matrixes and localization scores of all patients with BV. Seven loudspeakers located in a frontal semicircle in a horizontal plane at subject's head level were used, ranged from -90° to +90° in azimuth at intervals of 30°. In each trial, six stimuli were offered from each speaker in a random sequence, which makes a total of 42 stimuli. For each of the 42 stimulus presentations, the judged azimuth in response to a loudspeaker k was recorded (ψ_k) and plotted on this confusion matrix. The X-axis represents the target loudspeaker φ_k and de Y-axis represents judged azimuth ψk. Overlapping points are represented on the matrix by larger spheres, with a maximum size of 6 points and a minimum size of 1 point. Every point along the y = x line, represents a correct sound source identification. Root-mean-square error (RMSE) is calculated as the root-mean-square of the magnitudes of the differences between the azimuth angle of the sound presenting speaker (φ_k) and the azimuth angle of the judged speaker (ψ_k) across all 42 stimulus presentations. Mean absolute error (MAE) is the absolute error in degrees, divided by the total amount of stimulus presentations (i.e. 42 stimuli). The numbering of the subjects (S) corresponds to Table 2.

Graphics program used: PowerPoint (Microsoft)

Figure 4



a Bilateral vestibulopathy

MAE = 0.4°
RMSE = 4.6°

b Left-sided deafness

MAE = 60°
RMSE = 80°

c Healthy subjects

MAE = 0°
RMSE = 0°

Fig. 4 Examples of mean sound localization skills in (a) patients with BV, (b) patients with single-sided deafness and (c) healthy subjects with the respective confusion matrix. Seven loudspeakers located in a frontal semicircle in a horizontal plane at subject's head level were used, ranged from -90° to +90° in azimuth at intervals of 30°. In each trial, six stimuli were offered from each speaker in a random sequence, which makes a total of 42 stimuli. For each of the 42 stimulus presentations, the judged azimuth in response to a loudspeaker was recorded and plotted on this confusion matrix. The X-axis represents the target loudspeaker, and de Y-axis represents judged azimuth. Overlapping points are represented on the matrix by larger spheres, with a maximum size of 6 points and a minimum size of 1 point. Every point along the y = x line, represents a correct sound source identification. Root-mean-square error (RMSE) is calculated as the root-mean-square of the magnitudes of the differences between the azimuth angle of the sound presenting speaker and the azimuth angle of the judged speaker across all 42 stimulus presentations. Mean absolute error (MAE) is the absolute error in degrees, divided by the total amount of stimulus presentations (i.e. 42 stimuli).

Graphics program used: PowerPoint (Microsoft)

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Electronic Supplementary Material

Online Resource_1.xlsx