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Long-term evaluation of sound localisation in single-sided deaf adults fitted with a BAHA device

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Abstract

Objective: To perform a long-term evaluation of the localisation capabilities in the horizontal plane of single-sided deaf patients fitted with a BAHA device.

Design: Single-centre retrospective study.

Participants: Twenty-one adults with single-sided deafness (SSD) with normal hearing in the contralateral ear (pure tone average <20 dB, SDS > 90%) rehabilitated with a Cochlear BAHA device from 2003 to 2012 on the deaf side over a median follow-up of 8 years.

Outcome measures: The task used in this paper is a sound localisation identification task with a set-up of seven loudspeakers on a semi-circular array at 30-degree intervals performed at three periods: before BAHA, initially and at last follow-up. Our main criterion of judgement was the root-mean-square (RMS) localisation error. In addition, the Bern Benefit in Single-Sided Deafness Questionnaire (BBSS) was administered.

Results: The mean RMS localisation error was initially estimated at 64° without any rehabilitation (for a chance level RMS estimated at 81°). Initially, with the BAHA device, the RMS localisation error dropped to 51°. At the last follow-up evaluation, a significant decrease at 23° was noted. Concerning the Bern Questionnaire, 19% of the patients (n = 4) did not report any change (score of 0), 33% (n = 7) are satisfied (score of +1 or +2) and 48% (n = 10) are very satisfied with the BAHA device (score better than +3).

Conclusion: Improvement of sound localisation in the horizontal plane for some SSD patients is likely related to altered processing of monaural spectral cues. The time needed to learn to use the azimuth-dependent spectral cues takes time. Long-term follow-up should be considered for studies investigating sound localisation performance.

1 | INTRODUCTION

In the beginning of evolution of humans, our ability to localise the sources of sounds warned us initially of predators, explaining perhaps our specialisation in horizontal localisation. This ability to localise is probably associated with the development of high-frequency sensitivity.[1] Nowadays, our ability to localise warns up other danger (cars when crossing a road) and helps us sort out individual speech from the usual background noise. One knows that localisation is mainly based upon interaural differences in intensity and spectrum, and upon interaural differences in arrival time of features of the direct sound waveform.[2]

Subjects with single-sided deafness (SSD) have a single functioning cochlea and therefore cannot have access to the interaural time differences (ITD) and interaural level differences (ILD) cues. Ability to localise sound-source azimuth for SSD patients seems to be restricted to the hearing hemifield.[3] In addition, individuals SSD generally have scored higher on speech recognition in noise tasks particularly for conditions in which the target signal was presented from the side of the hearing loss.[4,5]

When Vaneecloo et al[6] proposed a bone-anchored device (ie BAHA) on the deaf side to rehabilitate the SSD, this indication was not as well accepted as now. In 2001, the results of a series of 29 patients were reported indicating that SSD patients fitted with a BAHA could provide benefits in hearing in noise, in better hearing from the deaf side and in localisation.[7] Several authors have confirmed hearing in noise benefits since that time but most of these studies did not demonstrate any improvement of sound localisation performance with BAHA and SSD.[4,8-18] On the other hand, some older studies show that in case of total deafness in one ear, localisation blur decreases with experience and localisation becomes more natural even without any rehabilitation.[19,20]

Despite the lack of objective evidence that BAHA can improve localisation performance in patients with SSD, some of these patients have reported subjectively that their localisation ability was improved with the device.[9,11] Other authors have pointed out that previous studies have not addressed the issue of how BAHA users might benefit in localisation by using head movements and attending to sounds for more extended times.[4] To explain this discrepancy, three hypotheses were proposed: (a) this impression is based mainly on the sound quality differences, (b) the lack of sensitivity of the performed localisation tests and (c) the learning effect of presenting additional azimuth-dependent spectral cues with the BAHA on to the good cochlea. Then, monaurally deaf listeners heavily relied on the head-shadow effect (especially with

Keypoints

- Subjects wih single side deafness have sound localization disorders.
- For SSD subjecst, BAHA device can improve sound localization performance.
- For SSD subjects, BAHA device give satisfaction to most patients.
- Subjects with BAHA device need several years to improve their hoizontal localization capabilities.
- For SSD subjects, BAHA device can improve hearing in noise.

TABLE 1 Characteristics of the studied population

Patient #	M/F	Age	Side	Aetiology	Onset of deafness (y)	Duration of deprivation (y)	Device
1	M	15	R	Congenital	0	7	Divino
2	F	19	L	Measles	5	5	Divino
3	M	50	L	Meningitis	7	37	Intenso
4	M	64	L	Fracture	52	2	Divino
5	M	61	R	Sudden deafness	56	1	Intenso
6	F	67	L	Labyrinthectomy	53	1	HC compact
7	F	57	R	Translab approach	45	2	HC compact
8	F	61	L	Translab approach	53	1	Intenso
9	F	25	L	Unknown	6	16	BP100
10	F	60	L	Ototoxic	46	6	Divino
11	M	60	L	Translab approach	54	1	Intenso
12	M	14	R	Congenital	0	10	Intenso
13	F	57	L	Translab approach	52	2	Intenso
14	M	33	L	Translab approach	31	1	BP100
15	M	45	R	Unknown	20	16	Divino
16	M	45	R	Fracture	6	29	Divino
17	M	21	L	Congenital	0	12	Divino
18	F	39	L	Congenital	0	32	Intenso
19	M	24	R	Fracture	18	2	BP100
20	F	54	L	Sudden deafness	49	1	HC compact
21	F	52	R	Congenital	0	43	HC compact

one fixed sound level), whereas binaural control listeners ignore this cue.[3] For Van Wanrooij et al, the apparent conflict in results from monaural listeners across different studies in the literature is probably attributable to two factors. First, a significant fraction of the listeners has not learned to incorporate spectral cues to extract azimuth location. Second, most studies did not use sufficient variation of stimulus intensities to enable a dissociation of the different contributions of the head-shadow effect and spectral cues.[3]

The aim of this study was to monitor the evolution of the ability of SSD patients with BAHA to localise in the horizontal plane after a long-term use.

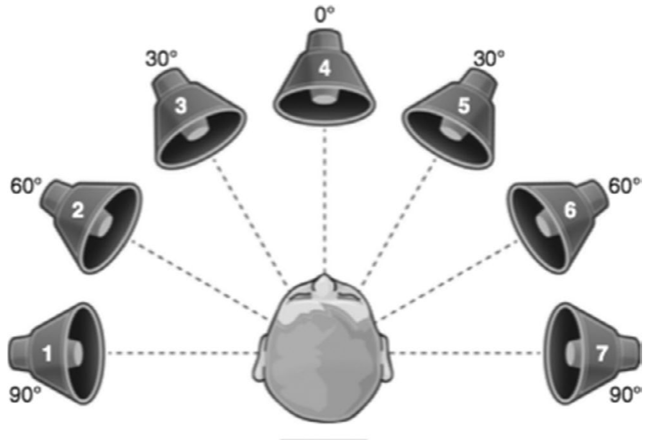

FIGURE 1 Set-up of the loudspeakers for localisation task

2 | METHODS

2.1 | Participants

Reviewing surgical records of our Department identified patients presenting a unilateral deafness who were rehabilitated with a Cochlear BAHA device on the deaf side (the patients rehabilitated with other bone conducting devices were excluded). In this population, we selected patients with normal contralateral hearing. Normal hearing was defined as following: PTA <20 dB and SDS > 90%. Eligible patients (n = 48) were offered the opportunity to participate in the study via a postal questionnaire. Twenty-one subjects accepted to come to our department for evaluation.

The mean age of the studied population is 44 years (median age: 50 years, range: 14-67 years). Depending on the aetiologies of deafness, the onset of SSD ranged from birth to 56 years with duration of deprivation ranging from 1 to 43 years. The age at implantation ranged subsequently from 7 to 72 years. The median follow-up for the 21 patients is 8 years (mean: 6.4 years). All the patients were using their device on a daily basis. The characteristics of the studied population are detailed in Table 1.

2.2 | Ethical considerations

The study was approved by the local ethical committee and has been performed according to the Declaration of Helsinki.

2.3 | Source localisation

The task used in this paper is a sound identification task. All testing was conducted in our near free-field booth. Seven loudspeakers were set-up on a semi-circular array at 30-degree intervals. The subject was seated such that his head was in the centre of, and in the same plane as the array of loudspeakers at a distance of approximately 1.5 m from the listener. Loudspeaker number 1 and 7 were, respectively, at azimuth 0-degree and 180-degree (at the left and the right of the patient; Figure 1). The subjects sat facing speaker number 4 and were allowed to move their head.

The BAHA settings were those used during usual day use. The stimulation consists of a 2 kHz narrowband sound with duration of approximately 1 second at 75 dB SPL. The stimulus was presented randomly three times per loudspeaker. The participants were asked to say the number of the speaker they thought the sound was coming from. Our main criterion to monitor localisation was the Root-Mean-Square (RMS) localisation error.

The rationale for choosing the RMS error to characterise the localisation error has been well described by Hartmann et al[21] RMS localisation error evaluates the average magnitude of the localisation errors, irrespective of the direction of that error.

Beside RMS error, per cent correct quantifies the probability that the patient identified the sound source perfectly, whereas RMS localisation error is a measure of overall accuracy. Perfect accuracy is represented by a RMS error of zero and 100% correct. A decrease in RMS error in a comparison of preoperative versus postoperative results shows an improvement in patients' ability to localise sound whereas an increase in RMS represents a decline.

The RMS localisation error is calculated by averaging the squared deviations of each patient's error (azimuth of the simulated position minus that of the identified location). Chance performance is indicated in our set-up by a RMS error of 81-degree angle (chance performance was computed via computer simulation across 1000 runs, in which the computer responded randomly using speaker numbers 1 to 7 as described previously with Monte Carlo statistics). [22]

Three measures were analysed: initially in unaided and aided conditions with the BAHA on a headset (performed during the preoperative assessment) and in aided conditions at the last evaluation.

2.4 | Speech recognition

Hearing in noise was tested with the noise (speech noise at 65 dB) coming from azimuth 0° and the speech (dissyllabic words) coming on the deaf side with and without the BAHA device (the preoperative testing was performed with a headset). The complete intensity/performance curve was traced. Changes in the Speech Reception Threshold (SRT) were noted.

2.5 | Subjective assessment of the device

The Bern Benefit in Single-Sided Deafness Questionnaire (BBSS) was administered for all the participants of the present study.[23] This questionnaire consists of 10 visual analogue scales rating the subjectively perceived benefit of the BAHA in different environments (eg: speech in quiet, TV or radio, Music, distant speaker, speech in noise, conversation in car, reverberant room, group conversation, sound localisation). For each question, the mark ranges from −5 (much more pleasant without the aid) to +5 (much more pleasant with the aid). This questionnaire has one question dealing with sound localisation performance (car horn).

2.6 | Statistical analysis

Data were collected in an Excel datasheet. Clinical features such as age at onset of deafness, cause of deafness, time of hearing deprivation were also collected. Values are given as Mean ± SE to the Mean (SEM) when otherwise specified. Statistical analyses were completed using GraphPad Prism 5.0 software. For multiple comparisons, we elicited a one-way ANOVA and post hoc test analysis (GraphPad Prism 5.0).

3 | RESULTS

3.1 | Localisation task

The mean error improved significantly when comparing pre- to post-implantation. Before implantation, the mean localisation error was less than 30-degree (equivalent to the interval between two adjacent loudspeakers), between 30-degree and 60-degree and more than 60-degree in, respectively, 15%, 33% and 52% of the subjects. Aided initially, the improvement was modest with a mean error of, respectively, 20%, 45% and 35% of the subjects. At last follow-up, the mean localisation error dropped dramatically, respectively, to 68%, 28% and 4% of the subjects. The RMS error changed from 64-degree in non-aided conditions to 51-degree in initially aided conditions and finally to 23-degree at last follow-up (Figure 2). The main factor related to the gain in localisation is the duration of use of the device (Figure 3).

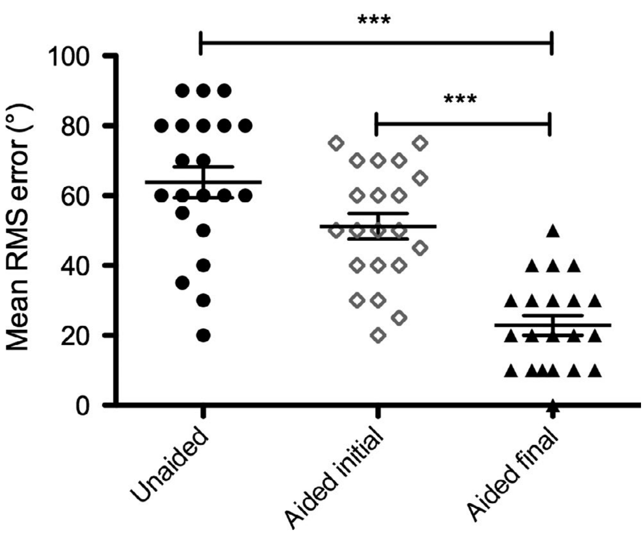

FIGURE 2 Evolution of the root-mean-square error of localisation over time

3.2 | Hearing in noise test

The mean initial unaided SRT was 60 dB. In aided conditions, the SRT was, respectively, estimated at 55 dB initially and at 53 dB at last evaluation (Figure 4). The exact shift of SRT between unaided conditions and in last aided conditions was 7.4 dB. No correlations were found between the improvement in localisation and the improvement in speech intelligibility in noise.

3.3 | Questionnaire scores

Concerning the Bern Questionnaire, no patients reported worse localisation performances with the BAHA device. All the responses ranged from 0 (no change) to +5 (much more pleasant with the BAHA device). Nineteen per cent of the patients (n = 4) did not report any change (score of 0), 33% (n = 7) are satisfied (score of +1 or +2) and 48% (n = 10) are very satisfied with the BAHA device (score better than +3). The mean score was +2.4 with a median score of +2.

4 | DISCUSSION

4.1 | Key findings and comparisons with other studies

Our study demonstrates significantly better horizontal localisation performances with time for patients with BAHA on the SSD side and normal hearing on the contralateral side, whereas the hearing in noise benefit (correction of the head shadow) is present initially. The

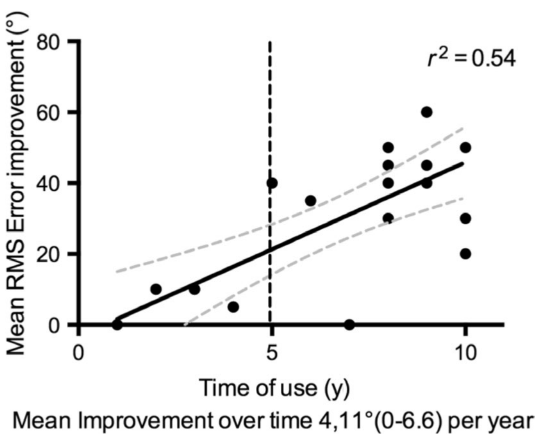

FIGURE 3 Evolution of the root-mean-square improvement relative to the duration of use of the device (some patients had the same rms improvement: 2 patients after 2, 3, 4, and 9 y resulting in 17 points for 21 patients)

questionnaire scores are in concordance with the localisation tests. The main difference with other studies that did not demonstrate any improved localisation performance with BAHA, and SSD is the length of the follow-up (median of 8 years in our study).

We hypothesised that this can be explained by the difficulty and the time necessary to take advantage of extra azimuth-dependent spectral information provided by the BAHA to the only hearing ear and to the central auditory pathway. SSD patients lacking the binaural acoustic differences rely on spectral pinna cues of their normal ear to localise.[24] Moreover, even it is ambiguous for unknown intensities, the acoustic head-shadow effect also serve heavily as monaural level cue with familiar acoustic environments in daily life.[3,25,26] So, the reported improvement is more likely related to adaptation and reweighting of monaural spectral pinna cues and therefore related to monaural processing. BAHA users might benefit as well in localisation by using head movements.[4] Very small head movements could produce detectable spectral changes, which could influence apparent position judgements in the free-field. SSD patients with BAHA are then supposed to learn how to localise via the help of extra azimuth-dependent spectral information to the only hearing ear and to the central auditory pathway. Azimuth-dependent spectral information coming from the sound source will reach the good ear and additional azimuth-dependent spectral information will come from the BAHA side then transferred with a slight delay to the good ear. The BAHA is then supposed to provide extra cues (even distorted and incomplete).

In this study, we have found a significant improvement of localisation other time in SSD patients with BAHA, which does not seem to be correlated with the hearing in noise benefit which in the other hand appears much sooner after the rehabilitation. However, a long period of adaptation and training is compulsory in order to observe this potential benefit. Daily training led to a progressive recovery in sound localisation accuracy in humans with altered spatial cues available by plugging one ear.[27] It could explain why some SSD patients with a long deprivation have developed rather good abilities to localise (ie congenital SSD) and do not complain from localisation issues. The benefit of training is driven by the auditory system and does not require a fully functioning visual system as shown in mature ferrets with one ear plugged.[28] Recording studies have shown that these adaptive adjustments take place in the superior colliculus of barn owls[29] and ferrets[30] that were raised with one ear plugged. There are other evidences of the existence of ongoing spatial calibration in human auditory system. After modifications of the outer pinnae with moulds in human subjects, elevation localisation is immediately degraded but accurate performance could be reacquired without interference of the neural representation of the original cues.[25]

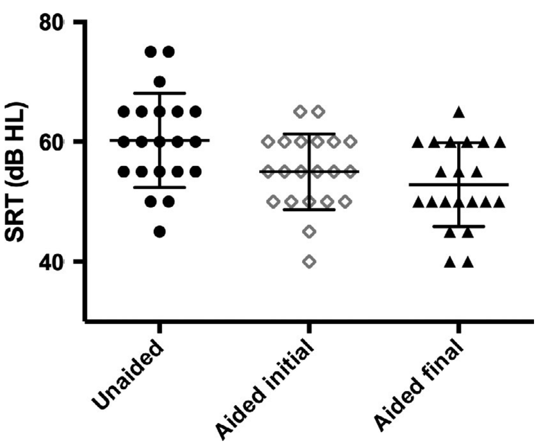

FIGURE 4 Evolution of the speech reception threshold in noise over time

Auditory-evoked potentials suggest that the adaptive shift in sound-azimuth response behaviour occurs gradually and may continue for at least 2 years.[31] This adaptive plasticity might be improved with a localisation-specific training protocol.[20] Evidence of the benefit of practice for sound localisation has been demonstrated as well in other situations (with and without sight).[32]

With a BAHA device, the spectral information is minimised by the fact that this device does not amplify sounds above 6 kHz. Finally, the test itself is based very little on the spectral indices since it uses a 2 kHz narrowband sound. Thus, the spectral information is not the only cause of improvement and is hardly tested with our set-up and there might be others causes of improvement.

The second source of potential improvement in localisation ability lies in temporal cues. With a BAHA on a SSD, there is the processing time plus the delay of transmission of sound from the BAHA device to the good ear. The time delay (around 0.6 ms) is not constant and varies irregularly with frequency.[33] It is noteworthy that there is evidence to support that human brain can adapt to the mismatched delays within hours or days.[27,28] It infers that if the mismatched processing time does not change too often, people may still be able to localise sounds using distorted temporal cues.

The third source of potential improvement in localisation ability lies in the fact that the BAHA device may participate via new proprioceptual inputs to the definition of the body map allowing modification of the sound depth perception as well as the sound localisation. Recent studies have pointed out the relationship between deafness and posture[34-36] with a higher incidence of postural changes in the spine. Concerning the relationship with motor performance, it has been reported that children with hearing loss had greater limitation when compared listeners in manual skills (62%), ball skills (52%) and body balance skills (45%).[37] We have also indications for some SSD patients that a postural sway may occur after placement of the BAHA device on the deaf side that may lead to a better postural stability.

We cannot completely be sure that the improvement of the localisation is exclusively related to the port of the BAHA device since we do not have a control group (SSD listener who were not implanted). However, patients could be considered as their own control with a median duration of SSD without BAHA of 5 years with still poor initial localisation skills. Even if we cannot exclude that the improvement after BAHA is due to learning, we observed that the patients had a lot of time to improve their skills with training and experience before the BAHA and it is not what our initial testing indicated in this series (most of the patients had poor initial localisation skills).

4.2 | Conclusion and impact of findings

In conclusion, we have reported on a series of 21 SSD patients with a BAHA device on the deaf side and normal hearing on the contralateral side. After a long follow-up (median of 8 years), we have observed a significant improvement in their horizontal localisation capabilities with our test set-up conditions and the Bern Questionnaire. It is interesting to note that the hearing in noise benefit, certainly due to the correction of the head-shadow effect, is not delayed.

The reasons of this delayed improvement in localisation have not actually been clarified. Our main hypothesis is that these patients enhance their localisation skills with azimuth-dependent acoustical cues and training. However, use of distorted temporal cues and construction of a new body map with the help of new proprioceptual inputs and sensory motor plasticity should be considered too. Finally, we cannot also rule out that these results are due to the test set-up and some learning effects. However, one should consider that the patients reported as well a benefit with the Bern Questionnaire which is more representative of an everyday localisation task. It is possible that the SSD subjects, because of being tested, realise they can use monaural cues in daily life, and therefore experience an improvement. That this improvement is related to monaural cues and not to the BAHA device, is something the SSD subjects might not be aware off. However, the patients with a median duration of their SSD status of 5 years had enough time without the BAHA to get used to the monaural cues coming to their normal ear but they still demonstrated poor localisation skills at initial testing. We should consider as well that the questionnaire echoes the feeling of improvement from the patients and therefore confirms the localisation tests.

Clinically, localisation training protocols should be developed and proposed to enhance the localisation capabilities. Short-term localisation study (<5 years) should be avoided when the main localisation cues (ITD, ILD) are not usable or present for the patient.

CONFLICT OF INTEREST

No conflict of interest relative to the work.

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