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Original article

Azimuthal sound source localization of various sound stimuli under different conditions

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ABSTRACT

Aim: To evaluate azimuthal sound-source localization performance under different conditions, with a view to optimizing a routine sound localization protocol.
Material and method: Two groups of healthy, normal-hearing subjects were tested identically, except that one had to keep their head still while the other was allowed to turn it. Sound localization was tested without and then with a right ear plug (acute auditory asymmetry) for each of the following sound stimuli: pulsed narrow-band centered on 250 Hz, continuous narrowband centered on 2000 Hz, 4000 Hz and 8000 Hz, continuous 4000 Hz warble, pulsed white noise, and word ("*lac*" (lake)). Root mean square error was used to calculate sound-source localization accuracy.
Results: With fixed head, localization was significantly disturbed by the earplug for all stimuli ($P < 0.05$). The most discriminating stimulus was continuous 4000 Hz narrow-band: area under the ROC curve (AUC), 0.99 [95% CI, 0.95–1.01] for screening and 0.85 [0.82–0.89] for diagnosis. With mobile head, localization was significantly better than with fixed head for 4000 and 8000 Hz stimuli ($P < 0.05$). The most discriminating stimulus was continuous 2000 Hz narrow-band: AUC, 0.90 [0.83–0.97] for screening and 0.75 [0.71–0.79] for diagnosis. In both conditions, pulsed noise (250 Hz narrow-band, white noise or word) was less difficult to localize than continuous noise.
Conclusion: The test was more sensitive with the head immobile. Continuous narrow-band stimulation centered on 4000 Hz most effectively explored interaural level difference. Pulsed narrow-band stimulation centered on 250 Hz most effectively explored interaural time difference. Testing with mobile head, closer to real-life conditions, was most effective with continuous narrow-band stimulation centered on 2000 Hz.

1. Introduction

Sound source localization is based on 3 main cues: 2 binaural (interaural time difference: ITD; interaural level difference: ILD) and 1 monaural spectral (head-related transfer function: HRTF) [1].

Individual performance can be assessed subjectively on stereo-audiometry; this was developed in Lille, France, by Gabriel Decroix and Jacques Dehaussy in the 1960s, and comprises all tests exploring stereophonic hearing (binaural hearing and hearing using a stereophonic device) [2–4]. Tests fall into three groups:

- spatial localization (Decroix test);
- spatial discrimination of speech in noise (Hirsh test [5]); and;
- multidirectional measurement of prosthetic gain (Dehaussy test).

Auditory asymmetry, defined by > 10 dB HL interaural difference in mean pure-tone threshold at 500, 1000, 2000 and 4000 Hz, impairs sound-source localization accuracy by impairing the binaural cues, thus impairing quality of life [6,7]. The contribution of stereo-audiometry has been highlighted for many years, both to indicate intervention and because the classical audiometry used by otosurgeons fails to take account of the full range of results of surgery in terms of social rehabilitation [4]. This is equally true for assessing how well binaural hearing has been restored by use of a stereophonic device [4]. Stereo-audiometry can also assess sound-source localization performance in unilateral hearing loss or any type of auditory asymmetry (post-lingual or congenital, conduction

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Table 1
Types of sound stimulus and corresponding localization indices.

Type of stimulus	Main localization indices explored
Pulsed narrow-band noise centered around 250 Hz	ITD (Envelope and Phase)
Continuous narrow-band noise centered around 2000 Hz	Zone of uncertainty
Continuous 4000 Hz pure-tone warble	ILD
Continuous narrow-band noise centered around 4000 Hz	ILD
Continuous narrow-band noise centered around 8000 Hz	ILD and HRTF
Pulsed white noise	All
Word ("*lac*")	All

Hz: Hertz; ITD: Interaural Time Difference; ILD: Interaural Level Difference; HRTF: Head-Related Transfer Function.

or sensorineural) under various types of rehabilitation (cochlear implant, bone-anchored hearing aid (BAHA) or conventional hearing aid) [8–11].

The present study objective was to assess localization of various sound stimuli under different conditions (with and without auditory asymmetry, and with head fixed or mobile), with a view to optimizing a routine sound-source localization protocol.

2. Material and method

The study population comprised young adult volunteers free of otoneurologic pathology, providing explicit consent to the study protocol as presented by the investigator more than 24 hours before testing (pre-inclusion information). The study period was August 2016 to March 2017.

Two groups were formed: the "Fixed Head" group kept their head still during testing, while the "Mobile Head" group were allowed to move it.

The design was an experimental study with cluster randomization, with the first half of the recruitment assigned to Fixed and second half to Mobile Head. Within each group, each subject served as their own control (classic sequential matching).

Testing was conducted in an anechoic soundproof booth (IAC Acoustics, Winchester, UK). Seven spherical coaxial speakers (Elipson Planet L; Elipson–AV-Industry, Champigny, France) were arranged in a frontal half-field (180°) about 1 meter from the listener, at 30° intervals, numbered 1 (−90° left) to 7 (+90° right). Sounds were generated by an AC40 clinical audiometer (Interacoustics, Middelfart, Denmark).

Three types of ear-plug (polyurethane foam; Howard Leight, Honeywell International Inc., San Diego, CA) were used, to better adapt to individual outer-ear morphology: Max® (single number rating (SNR), 37), Max Lite® (SNR, 34), and Bilsom® 303L (SNR, 33). SNR is an attenuation index averaged over all frequencies, as defined by the International Standards Organization (ISO 4869-2).

Narrow-band stimuli were used, to better explore localization indices, as broad-band sound localization is not affected by which binaural localization cue is used [12].

In the light of what is known about sound localization physiology, different stimuli were tested to explore different localization indices [1] (Table 1). A low frequency (< 1000 Hz) explores ITD according to phase. For pulsed sounds, the perceived difference in arrival time of the sound envelope between the two ears, sometimes known as the interaural envelope difference, is also assessed (phase detection). For intermediate frequencies (1000–3000 Hz), ITD and ILD sensitivity is lower. High-frequency pure tones (> 3000 Hz) explore ILD. Complex high-frequency sounds (especially > 7000 Hz) explore ILD and HRTF. Pulsed white noise explores all indices, as does a word speech stimulus. For the speech stimulus, a short signal delivered by a male voice was used, as in Grantham et al.'s study [8], chosen from J.E. Fournier's monosyllabic word-list: "*lac*" (the French word for "lake", pronounced like "lack").

Participants were acclimatized by listening to white noise through speakers nº 1 (−90°), nº4 (0°) and nº7 (+90°). All were seated. One group ("Fixed") kept their head still in a head-stall, while the other ("Mobile") were allowed to move their head. Stimulus level was 60 dB HL: i.e., comfortable. Subjects were asked to say the number of the speaker that they thought was the source.

Each of the above-listed stimuli was presented 3 times per speaker: i.e., 21 times in all, in random order to prevent habituation.

Continuous sounds, exploring ILD, were presented by progressively turning off speakers, leaving only one emitting the sound, to avoid detection of the start of the acoustic envelope.

Testing was performed first without and then with a right ear plug (acute auditory asymmetry).

For a given speaker (k), the following were calculated [12–14]:

Mean error, E (°):

$$E(k) = \frac{A}{M} \cdot \sum_{i=1}^{M} (r_i - k)$$

$$E(k) = \frac{A}{M} \cdot \sum_{i=1}^{M}$$

where A is the angle between 2 speakers (30°), M the number of trials per speaker ($N = 3$), r_i the response (speaker 1 to 7 reported) on trial i, k the actual speaker number (1 to 7), so that $e_i = r_i - k$: i.e., error on trial i.

Root mean square error *(RMS Error)*, D (°):

$$D(k) = \sqrt{[E(k)]^2}$$

$$D(k) = \sqrt{\left[\frac{A}{M} \cdot \sum_{i=1}^{M} e_i\right]^2}$$

$$D(k) = \sqrt{\frac{A^2}{M} \cdot \sum_{i=1}^{M} (e_i)^2}$$

$$D(k) = A \cdot \sqrt{\frac{\sum_{i=1}^{M} (e_i)^2}{M}}$$

Mean response:

$$R(k) = \frac{\sum_{i=1}^{M} r_i}{M}$$

And standard deviation:

$$S(k) = \sqrt{\frac{\sum_{i=1}^{M} [r_i - R(k)]^2}{M}}$$

RMS Error (D), in degrees (°), was used to assess sound-source localization accuracy. Yost et al. showed that RMS Error best represented sound-source localization accuracy [12]. The calculation was that reported by Hartmann and used by Yost et al. [12,13,15,16].

Statistical tests were performed on Prism software, version 6.0e (GraphPad Software Inc., La Jolla, CA). Results were reported as

Table 2
Characteristics of the 2 groups.

	Groups		Exact *P*-value
	Fixed Head	Mobile Head	
Number (n)	15	15	
Sex ratio M/F	8/7	7/8	
Handedness R/L	13/2	13/2	
Mean age (years)	24.2 ± 3.65	24.3 ± 3.17	0.7657 (NS)
MPTT right (dB HL)	1.42 ± 2.95	1.42 ± 2.87	0.7962 (NS)
MPTT left (dB HL)	1.42 ± 3.56	1.42 ± 3.20	0.6718 (NS)
MPTT right with plug (dB HL)	40 ± 3.84	40.91 ± 3.80	0.6117 (NS)

Results reported as mean ± standard deviation. M/F: Male/Female; R/L: Right/Left; MPTT: mean pure-tone threshold (mean of thresholds at 500, 1000, 2000 and 4000 Hz); dB HL: deciBel Hearing Level; NS: non-significant ($P > 0.05$). Comparisons on non-parametric Mann–Whitney rank test for independent samples.

mean ± standard deviation. The significance threshold was set at $P < 0.05$.

Given the small group-sizes (15: i.e., < 30), non-parametric (rank) tests were used. For matched samples (with vs. without ear-plug, subjects serving as their own control) the non-parametric Wilcoxon–Mann–Whitney signed ranks test or non-parametric Friedman test was used, with Dunn correction for multiple comparison (multiple comparison of matched samples from the same population). For unmatched samples (Fixed vs. Mobile groups), the non-parametric Mann–Whitney test was used.

Test discrimination capacity (screening and diagnosis) was assessed on ROC (Receiver Operating Characteristics) curve.

Screening was assessed in the most difficult of the conditions (stimulus delivered by the speaker on the hearing-loss side: i.e., plugged right ear), to determine which stimulus showed the best sensitivity and specificity for screening with a threshold of ≥ 2 errors (i.e., ≥ 60° error). Diagnosis was assessed on the test as a whole (all speakers) with a threshold of ≥ 1 error (i.e., ≥ 30° error).

The Monte Carlo method [17] was used to calculate chance performance (RMS Error) by random generation of 1000 responses repeated 100 times for each speaker. Overall chance RMS Error (as though the subject always responded randomly) was found to be 82.8 ± 4.2°.

3. Results

3.1. Study population

Thirty healthy volunteers were included, 15 in the Fixed and 15 in the Mobile group, with comparable age, handedness and hearing (Table 2).

Pure-tone thresholds were comparable between ears (i.e., no auditory asymmetry). The right ear-plug provided relatively homogeneous attenuation across frequencies, with thresholds around 40 dB HL in both groups.

3.2. "Fixed head" group

For each stimulus, RMS Error was greater with the test speaker on the hearing-impaired side (Fig. 1). Three stimuli seemed most difficult to localize with a plugged ear (i.e., high RMS Error): continuous narrow-band noise centered around 2000 Hz, continuous narrow-band noise centered around 4000 Hz, and continuous narrow-band noise centered around 8000 Hz (Fig. 1). Pulsed noise (narrow-band 250 Hz, white noise, and word) was less difficult to localize with a plugged ear (i.e., lower RMS Error). The continuous 4000 Hz warble was difficult to localize without and even more with the right ear plugged (Fig. 1).

Overall, RMS Error on all speakers was significantly greater with than without the right ear-plug, for all stimuli: $P = 0.0001$ for continuous 4000 Hz warble, $P = 0.0002$ for pulsed white noise, and $P < 0.0001$ for the others, on Wilcoxon–Mann–Whitney signed ranks test for matched data (Fig. 2).

Continuous narrow-band noise centered around 4,000 Hz showed the best characteristics for both screening and diagnosis (Table 3).

3.3. "Mobile head" group

For each stimulus, RMS Error was greater with the test speaker on the hearing-impaired side (Fig. 3). Three stimuli seemed most difficult to localize with a plugged ear (i.e., high RMS Error): continuous narrow-band noise centered around 2000 Hz, continuous narrow-band noise centered around 4000 Hz, and continuous 4000 Hz warble (Fig. 3). Pulsed noise (narrow-band 250 Hz, and especially white noise) was less difficult to localize with a plugged ear (i.e., lower RMS Error). The word "*lac*" was difficult to localize with the right ear plugged. The continuous 4000 Hz warble was the only stimulus difficult to localize with the ear unplugged (Fig. 3).

Overall, RMS Error on all speakers was significantly greater with than without the right ear-plug, for all stimuli: $P = 0.0010$ for pulsed narrow-band 250 Hz, $P = 0.0002$ for continuous narrow-band 8000 Hz and for the word "*lac*", $P = 0.0039$ for pulsed white noise, and $P < 0.0001$ for the others, on Wilcoxon–Mann–Whitney signed ranks test for matched data (Fig. 4).

Continuous narrow-band noise centered around 2000 Hz and around 4000 Hz showed the best screening and diagnostic characteristics (Table 4).

3.4. Comparison between "Fixed head" and "Mobile head" groups

The two groups were comparable (Table 2) (except for head mobility).

Localization error with plugged ear was systematically smaller when the head was mobile, and significantly so, on Mann–Whitney tests for independent samples, for continuous 4000 Hz warble ($P = 0.0101$), continuous narrow-band 4000 Hz ($P = 0.0203$) and continuous narrow-band 8000 Hz ($P = 0.0011$) (Fig. 5). Word source localization was non-significantly poorer with mobile head. Stimuli with little impairment of localization (pulsed narrow-band 250 Hz and pulsed white noise) showed suggestively better localization with mobile head, but without significant difference due to the small number of errors concerned. Continuous narrow-band 2,000 Hz noise was also non-significantly better localized with mobile head.

4. Discussion

The present study included 30 healthy volunteers (15 per group), which may seem insufficient, but is reasonable compared to other studies of sound localization: 5 patients with external ear canal atresia for Vyskocil et al. [11]; 8 (experiment 1) and 16 (experiment 2) normal-hearing subjects for Wood and Bizley [18]; 4 [14] or 5 normal-hearing subjects [19] for Hartmann and Rakerd; 6 normal-hearing subjects for Cooper et al. [20]; 12 normal-hearing subjects in 2 groups of 6 for Irving and Moore [21]; one group of 8 and one of 9 normal-hearing males for Honda et al. [22]; 12 subjects (7 with unilateral sensorineural hearing loss and 5 with conduction hearing loss) [9] or 22 cochlear implant patients [8] for Grantham and Haynes; 45 normal-hearing subjects for Yost et al. [12]; and 57 normal-hearing subjects, 17 with bilateral conventional hearing aids, 8 with bimodal fitting (conventional plus contralateral cochlear implant), 32 bilateral cochlear implant patients and 8 hearing-preservation CI listeners for Dorman et al. [10].

We used non-parametric tests, which are lower-powered. Some authors (Vyskocil et al. [11] in 5 patients) assume a normal

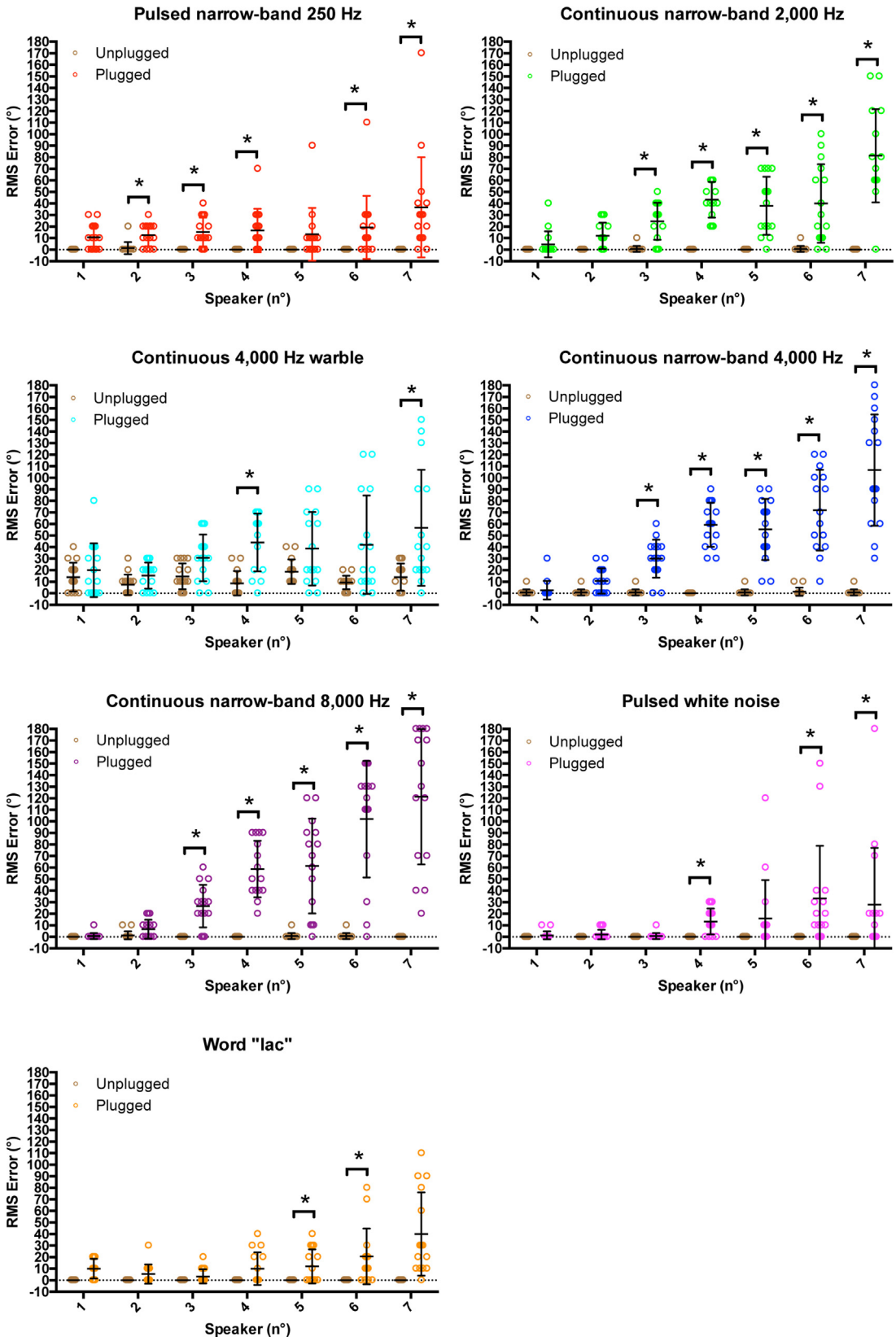

Fig. 1. Root mean square error (RMS Error) according to sound stimulus, ears unplugged (brown) then right ear plugged (colors) in 15 subjects, head fixed. For each condition and each speaker, 15 values were collected and reported as mean ± standard deviation. Asterisks (*) indicate speakers for which RMS Error differed significantly between plugged and unplugged right ear conditions (Friedman test with Dunn correction for multiple comparison).

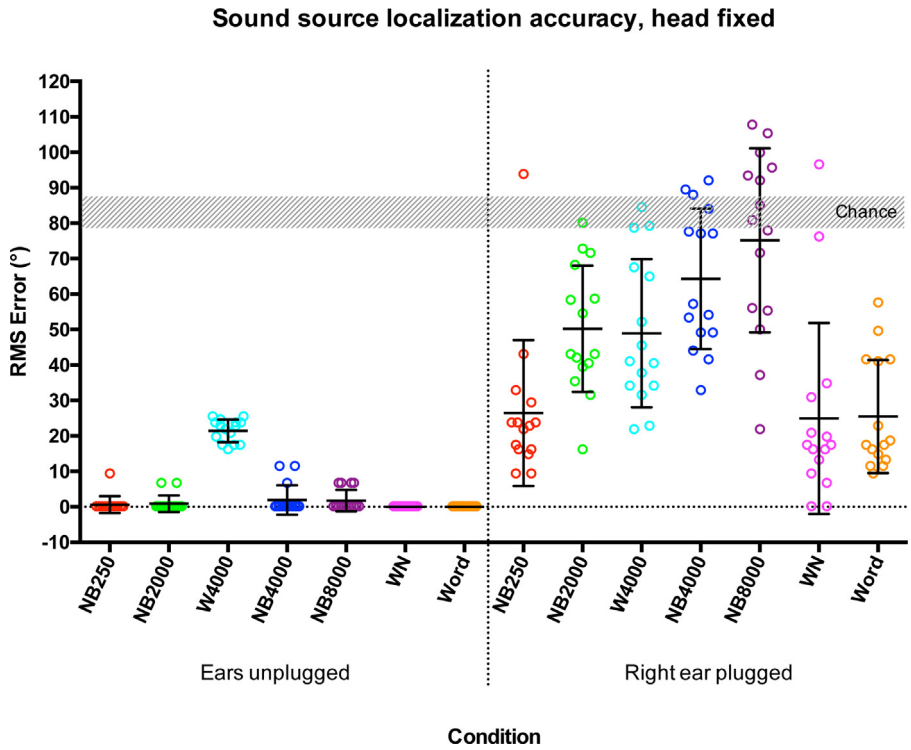

Fig. 2. Overall root mean square error (RMS Error), over all 7 speakers tested 3 times each, according to sound stimulus, ears unplugged then right ear plugged in 15 subjects, head fixed. The difference between the ears unplugged and right ear plugged conditions was significant for all stimuli (Wilcoxon–Mann–Whitney signed ranks test). Gray-hatched zone represents performance with random response (Chance). RMS Error: Root Mean Square Error; NB250: Pulsed narrow-band 250 Hz; NB2000: Continuous narrow-band 2000 Hz; W4000: Continuous 4000 Hz warble; NB4000: Continuous narrow-band 4000 Hz; NB8000: Continuous narrow-band 8000 Hz; WN: Pulsed white noise; Word: Word "*lac*".

Table 3
Screening discrimination (on speaker n°7 ipsilateral to hearing impairment, head fixed, at threshold of ≥ 2 errors) and diagnostic test (on all speakers, at threshold of ≥ 1 error) according to sound stimulus with fixed head.

Stimulus	Screening			Diagnosis		
	AUC [95% CI]	Threshold ≥ 2 errors (%)		AUC [95% CI]	Threshold ≥ 1 error (%)	
		Sensitivity [95% CI]	Specificity [95% CI]		Sensitivity [95% CI]	Specificity [95% CI]
Pulsed NB 250 Hz	0.82 [0.73–0.91]	26.67 [14.60–41.94]	0.72 [0.68–0.76]	0.72 [0.68–0.76]	45.40 [39.81–51.07]	99.37 [97.73–99.92]
Continuous NB 2.000 Hz	0.94 [0.89–0.99]	73.33 [58.06–85.40]	0.81 [0.77–0.84]	0.81 [0.77–0.84]	61.59 [55.97–66.99]	99.37 [97.73–99.92]
Continuous W 4.000 Hz	0.74 [0.63–0.84]	44.44 [29.64–60.0]	0.69 [0.65–0.73]	0.69 [0.65–0.73]	66.98 [61.49–72.15]	61.27 [55.65–66.68]
Continuous NB 4.000 Hz	0.99 [0.96–1.01]	80.0 [65.40–90.42]	0.85 [0.82–0.89]	0.85 [0.82–0.89]	72.06 [66.76–76.95]	97.78 [95.48–99.10]
Continuous NB 8.000 Hz	0.97 [0.92–1.01]	80.0 [65.40–90.42]	0.82 [0.79–0.86]	0.82 [0.79–0.86]	65.40 [59.86–70.64]	98.73 [96.78–99.65]
Pulsed white noise	0.70 [0.59–0.81]	15.56 [6.49–29.46]	0.64 [0.59–0.68]	0.64 [0.59–0.68]	27.62 [22.75–32.91]	100.0 [98.84–100.0]
Word "*lac*"	0.83 [0.74–0.92]	31.11 [18.17–46.65]	0.67 [0.63–0.72]	0.67 [0.63–0.72]	34.60 [29.36–40.14]	100.0 [98.84–100.0]

AUC: area under Receiver Operating Characteristics curve; 95% CI: 95% confidence interval; NB: Narrow Band; W: Warble; Hz: Hertz.

distribution in order to implement ANOVA [11]. ANOVA is in fact widely used, whether numbers are small [9,18,21,22] or not [10,12]. In other cases, t tests were used despite small sample size [8,19,20].

Unilateral ear-plugging gave a mean pure-tone threshold of 40 dB HL, and thus auditory asymmetry (i.e., > 10 dB HL) [6].

The study confirmed that sound localization is impaired in case of acute auditory asymmetry (with the ear-plug), especially when stimulus delivery is to the impaired side.

The main index of impaired localization is ILD, as shown by the greater errors found with continuous narrow-band noise centered around 4000 or 8000 Hz.

ITD (pulsed narrow-band noise centered around 250 Hz) was less disturbed, probably because the time difference between the ears was still perceived with a stimulus at 60 dB HL for a mean 40 dB HL impairment.

The continuous warble around 4000 Hz was a poor stimulus, leading to localization error even in normal-hearing subjects, probably because its frequency varies periodically around the carrying frequency, inducing ambiguous ILD perceptual coordinates. However, a non-warbled pure tone in free field would not be a relevant condition, due to formation of stationary waves liable to induce intensity variations in space of around 20 dB. We therefore advise against using pure-tones, whether warbled or not, in stereo-audiometry.

Continuous narrow-band noise centered around 2000 Hz was the most difficult to localize with mobile head, and with little difference whether the head was mobile or not. This is because the stimulus is right in the middle of the uncertainty zone between 1000 and 3000 Hz in which both ITD and ILD are relatively ineffective [23–26].

Localization for continuous narrow-band noise around 8000 Hz was especially improved by allowing head movement, due to accumulation of HRTF, particularly present at high frequencies (notably > 7000 Hz) [1].

Poorer localization of the speech stimulus "*lac*" was suggested (although not significant) with mobile head. This was because the

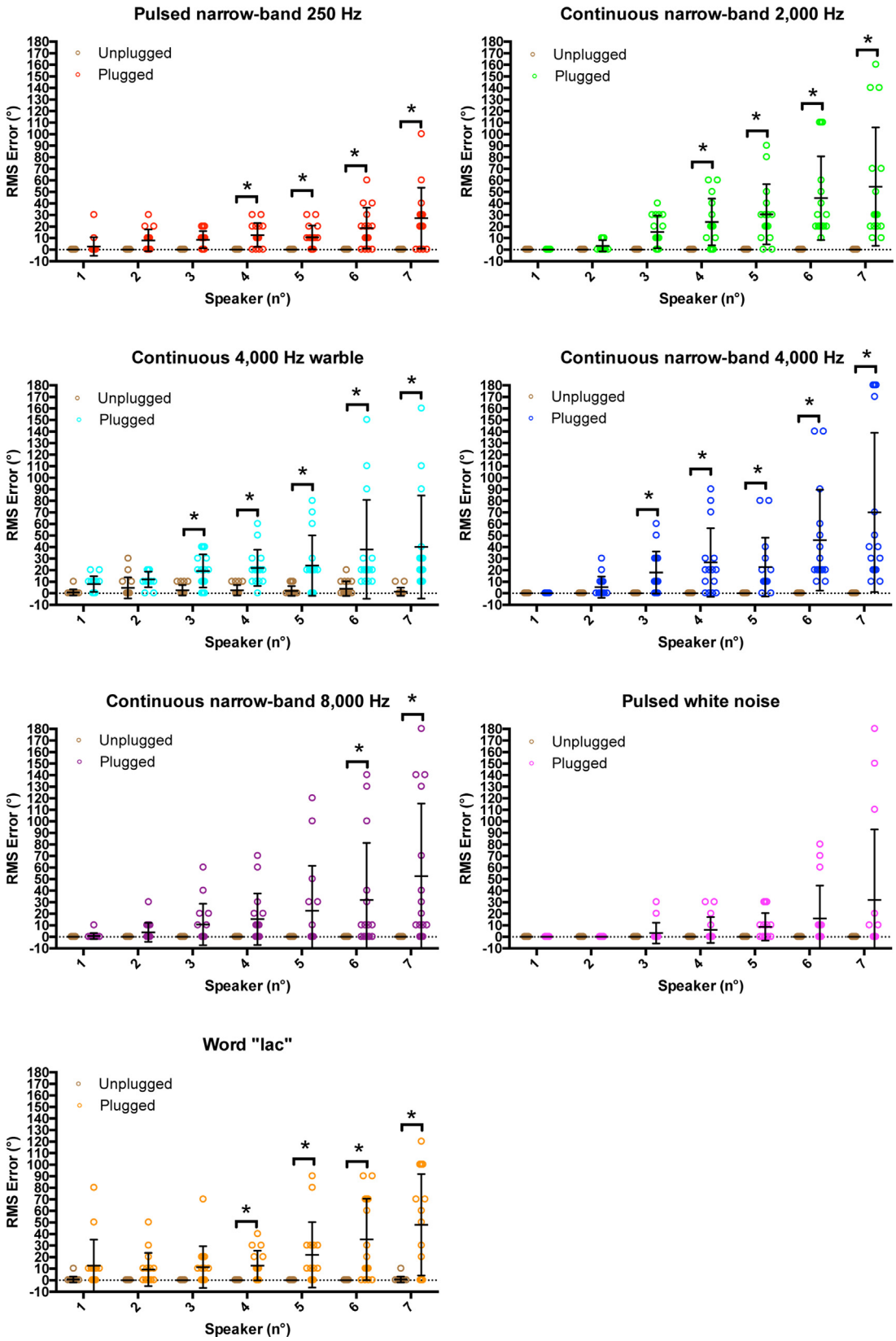

Fig. 3. Root mean square error (RMS Error) according to sound stimulus, ears unplugged (brown) then right ear plugged (colors) in 15 subjects, head mobile. For each condition and each speaker, 15 values were collected and reported as mean ± standard deviation. Asterisks (*) indicate speakers for which RMS Error differed significantly between plugged and unplugged right ear conditions (Friedman test with Dunn correction for multiple comparison).

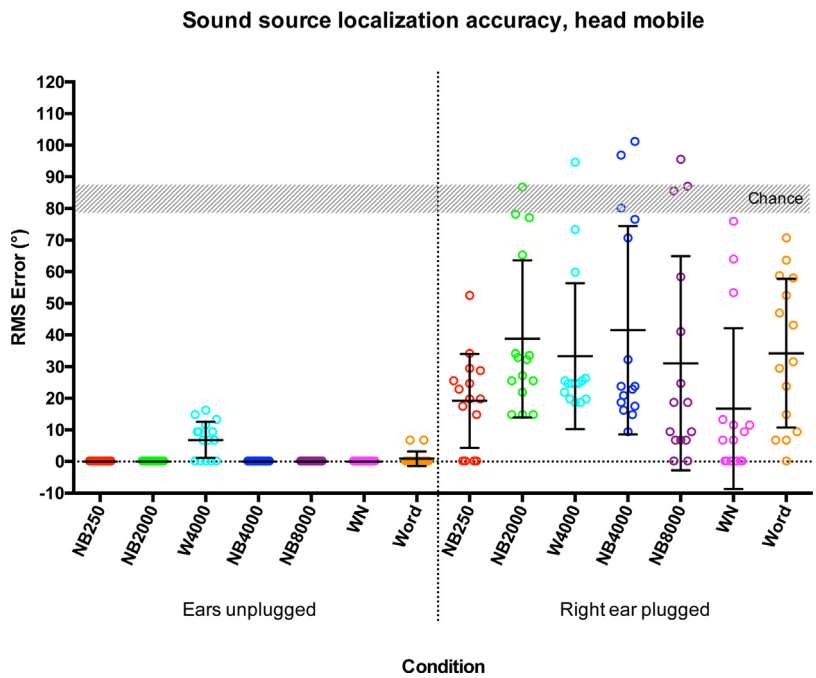

Fig. 4. Overall root mean square error (RMS Error), over all 7 speakers tested 3 times each, according to sound stimulus, ears unplugged then right ear plugged in 15 subjects, head mobile. The difference between the ears unplugged and right ear plugged conditions was significant for all stimuli (Wilcoxon–Mann–Whitney signed ranks test). Gray-hatched zone represents performance with random response (Chance). RMS Error: Root Mean Square Error; NB250: Pulsed narrow-band 250 Hz; NB2000: Continuous narrow-band 2000 Hz; W4000: Continuous 4000 Hz warble; NB4000: Continuous narrow-band 4000 Hz; NB8000: Continuous narrow-band 8,000 Hz; WN: Pulsed white noise; Word: Word "*lac*".

Table 4
Screening discrimination (on speaker n°7 ipsilateral to hearing impairment, head fixed, at threshold of ≥ 2 errors) and diagnostic test (on all speakers, at threshold of ≥ 1 error) according to sound stimulus with mobile head.

Stimulus	Screening			Diagnosis		
	AUC [95% CI]	Threshold ≥ 2 errors (%)		AUC [95% CI]	Threshold ≥ 1 error (%)	
		Sensitivity [95% CI]	Specificity [95% CI]		Sensitivity [95% CI]	Specificity [95% CI]
Pulsed NB 250 Hz	0.82 [0.73–0.91]	15.56 [6.49–29.46]	100.0 [92.13–100.0]	0.68 [0.64–0.72]	35.56 [30.27–41.12]	100.0 [98.84–100.0]
Continuous NB 2.000 Hz	0.90 [0.83–0.97]	51.11 [35.77–66.30]	100.0 [92.13–100.0]	0.75 [0.71–0.79]	49.84 [44.19–55.50]	100.0 [98.84–100.0]
Continuous W 4.000 Hz	0.81 [0.71–0.90]	28.89 [16.37–44.31]	100.0 [92.13–100.0]	0.74 [0.70–0.78]	55.24 [49.56–60.82]	91.43 [87.77–94.28]
Continuous NB 4.000 Hz	0.91 [0.84–0.98]	44.44 [29.64–60.0]	100.0 [92.13–100.0]	0.74 [0.70–0.78]	47.30 [41.68–52.98]	100.0 [98.84–100.0]
Continuous NB 8.000 Hz	0.78 [0.68–0.88]	33.33 [20.0–48.95]	100.0 [92.13–100.0]	0.65 [0.61–0.70]	30.79 [25.74–36.21]	100.0 [98.84–100.0]
Pulsed white noise	0.64 [0.53–0.76]	20.0 [16.37–44.31]	100.0 [92.13–100.0]	0.58 [0.54–0.63]	16.51 [12.58–21.08]	100.0 [98.84–100.0]
Word "*lac*"	0.78 [0.68–0.88]	46.67 [31.66–62.13]	100.0 [92.13–100.0]	0.69 [0.65–0.74]	39.37 [33.93–45.00]	99.37 [97.73–99.92]

AUC: area under Receiver Operating Characteristics curve; 95% CI: 95% confidence interval; NB: Narrow Band; W: Warble; Hz: Hertz.

word was too short for head rotation to be able to accumulate relevant indices; performance actually deteriorated. This finding is compatible with those of Cooper et al., who showed that stimulus presentation during rotation reduced sound-source localization accuracy [20]. Likewise, source movement detection is poorer during head rotation [22].

The present findings are inconclusive regarding the model of acute auditory asymmetry by conduction hearing loss. The most relevant stimuli (intellectually and/or experimentally) should be tested under pathologic conditions of unilateral total deafness or chronic conduction hearing loss, with or without rehabilitation: i.e., pulsed narrow-band 250 Hz for ITD and continuous narrow-band 4000 Hz for ILD.

Head movement improved localization capability. The fixed head condition, on the other hand, being the most difficult condition for the subject, more easily detects localization impairment. Several teams working on sound localization use the fixed head condition [11,12,14,18,19,21]. In the case of BAHA rehabilitation, Grantham et al. found no difference in localization ability according to head mobility or not [9].

There are thus two possibilities, depending on where the emphasis is placed:

- fixed head testing, under the most difficult conditions, most likely to detect localization impairment; and/or;
- mobile head testing, which is closer to real-life conditions.

Limiting edge effects by not using the outermost speakers (here, n°I and n°7), unbeknown to the listener, was not feasible in the present study as it would have left only 5 speakers. The technique is used by teams that have more speakers in the anterior half-field: 13, every 15°, for Yost and Dorman [12]; 18, every 15°, for Wood and Bisley [18]; 33 or 43 for Grantham et al. [8,9]; 25 for Hartmann [19]. The technique gives larger errors, as it designates the outermost speakers as possible sources, although they are not. We did not reduce the number of active speakers, as at least 6 are needed to obtain globally reliable results according to Hartmann et al. [14]. Even so, some teams seem to obtain reliable results with just 5 speakers [27,28], or even 2 speakers at 90° left and right in under-9 year-olds, for whom 7 speakers at 30° intervals

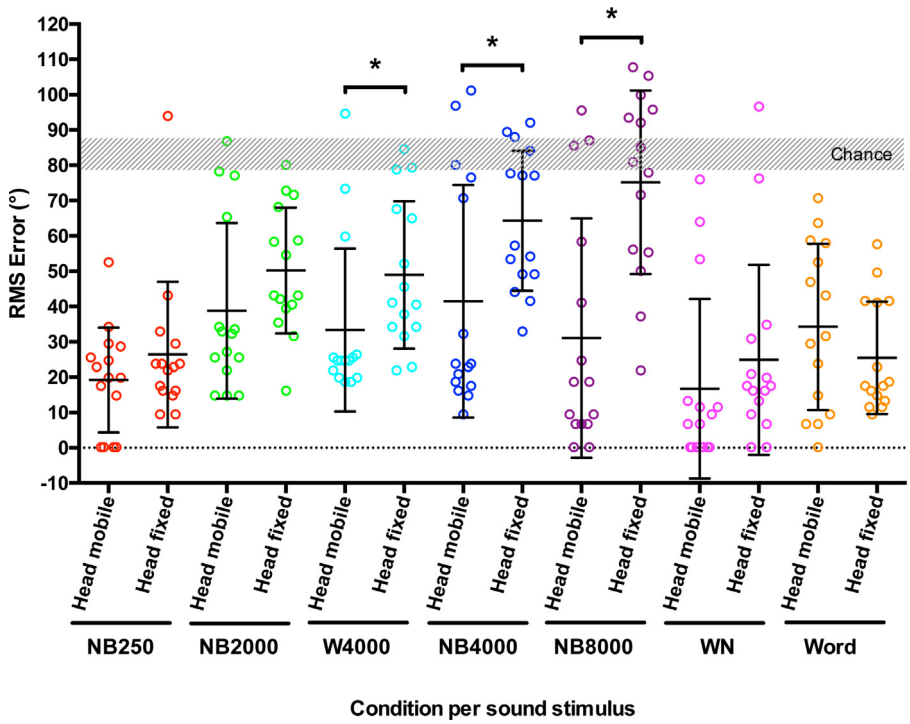

Fig. 5. Overall root mean square error (RMS Error), over all 7 speakers tested 3 times each, according to sound stimulus, head mobile ($N = 15$) and head fixed ($N = 15$). Asterisks (*) indicate significant difference at $P < 0.05$ on Mann–Whitney ranks test. Gray-hatched zone represents performance with random response (Chance). RMS Error: Root Mean Square Error; NB250: Pulsed narrow-band 250 Hz; NB2000: Continuous narrow-band 2000 Hz; W4000: Continuous 4000 Hz warble; NB4000: Continuous narrow-band 4000 Hz; NB8000: Continuous narrow-band 8000 Hz; WN: Pulsed white noise; Word: Word "*lac*".

seems too complicated; but in this case it is lateralization more than localization that is being assessed [29].

5. Conclusion

In the light of the present results and analysis of the literature, we propose the following protocol for azimuth sound localization:

- head immobile at 0° face to speaker n°4:
  - screening by continuous narrow-band noise centered around 4000 Hz, delivered by the speaker on the more impaired side (no1 or no7), progressively switching off the others:
    - if ≤ 1 error (≤ 30°): no major localization impairment; test continued at examiner's discretion,
    - if ≥ 2 errors (≥ 60°): very probable localization impairment requiring full diagnostic testing;
  - diagnosis:
    - continuous narrow-band noise centered around 4,000 Hz, delivered randomly by all 7 speakers, progressively switching off the others; mainly explores ILD,
    - pulsed narrow-band noise centered around 250 Hz, delivered randomly by all 7 speakers, progressively switching off the others; mainly explores ITD.

Testing can be with mobile head to approximate real-life conditions at the cost of reduced sensitivity to localization impairment. In that case, continuous narrow-band noise around 2000 Hz can be used for screening and then diagnosis.

Disclosure of Interest

The authors declare that they have no competing interests.

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