Contribution of a method of assessing minimum audible angle in headphones

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A B S T R A C T

Objectives: The main objective of this study was to test the feasibility of measuring minimum audible angle in headphones with different reference positions in the horizontal plane, and comparing different types of pre-recorded head-related transfer functions. The secondary objective was to assess spatial discrimination performance in simulated unilateral hearing loss by measuring the minimum audible angle under monaural conditions using headphones.

Materials and methods: Minimum audible angle was assessed in 27 normal-hearing subjects, to test their spatial discrimination abilities, using 4 datasets of pre-recorded head-related transfer functions: 2 recorded on mannequins (KU100, KEMAR), and 2 individualized head-related transfer function datasets (TBM, PBM). Performance was evaluated at 3 reference positions (0°, 50° and 180°) in 1 binaural and 2 monaural conditions.

Results: KU100 generated minimum audible angle values smaller than KEMAR in frontal and lateral position ($P < 0.005$), with a suggestive difference ($P < 0.05$) compared to TBM and PBM in the frontal and lateral planes. Comparison between binaural and monaural conditions showed significant differences in frontal position for MON-c (contralateral) and MON-i (ipsilateral) ($P < 0.001$), in lateral position for MON-c only ($P < 0.001$) and in posterior position for MON-c and MON-i ($P < 0.001$).

Conclusion: This study suggests that evaluation of spatial discrimination capacity using minimum audible angle with the KU100 head-related transfer dataset was reliable and robust.

1. Introduction

Spatial discrimination has generally been assessed using the minimum audible angle (MAA), defined as the minimum detectable angle between 2 sound sources [1]. Free-field discrimination performance was best in central position and was generally between 5° for young adults and 10° for older subjects [2]. MAA was seldom measured in free field, as this requires complex equipment: either several loudspeakers with identical physical characteristics [3], or a single speaker with precisely controlled movement, making MAA measurement technically demanding. Whatever the equipment, it required a large number of measurements and a big effort of concentration for hearing-impaired subjects [1,4,5]. Simulated sound source spatialization via headphones could make this easier, and has been implemented using pre-recorded head and outer ear

related transfer functions, to get around the drawbacks of free-field conditions [6].

The main aim of the present study was to assess the feasibility of MAA measurement via headphones in different horizontal positions, comparing several types of pre-recorded head-related transfer function (HRTF), taken either from databases of HRTFs pre-recorded on 2 mannequins or else individualized: i.e., based on real measurements in human subjects. Comparison identified the type of HRTF giving MAA measurements that were the closest to those made in free field.

The secondary objective was to assess spatial discrimination performance under simulated unilateral hearing loss, by measuring MAA under monaural conditions via headphones.

2. Material and methods

To assess the feasibility of MAA measurement via headphones using pre-recorded HRTFs, measurements using different types of HRTF were made in 27 normal-hearing subjects, aged 18–25 years,

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with audiometric confirmation of normal and symmetrical thresholds at 250–6000 Hz. Written informed consent was secured.

Sound stimuli were delivered via in-ear headphones (Pioneer SE-CH5TK), as used for prior HRTF recording in mannequins. Before each stimulus block, a training session was conducted to familiarize subjects with the horizontally spatialized sound source simulation.

Stimuli comprised 2 types of spatialized sound, with 500 ms inter-stimulus interval: a standard sound emanating from the reference position (0°, 50° or 180°), and deviant sounds from another position. Subjects were to determine whether the sounds came from the same angular position (by clicking on 0) or different positions (by clicking on 1).

At first, the deviant stimulus was at 50° to the left of the reference position, then varied by 5° steps according to the subject's responses. In case of false response, the distance increased by 5°. After 3 false responses, the deviant sound came back to the initial 50° separation. In case of correct response, the deviant sound approached the reference by 5° steps; if all responses were correct, up to MAA close to 0°, the deviant sound came back to the initial 50° separation. The procedure stopped after 36 trials.

Four types of HRTF were used: non-individualized, taken from databases of measurements made on the mannequin heads KEMAR [7] and KU100 [8], and individualized HRTFs from 48 human subjects with anthropometric data available online at <https://www.sofaconventions.org> [6]. HRTFs are classically measured recording a sound from 2 microphones at the entry to the outer ear canal of the subject or mannequin [6]. KU100 is a database comprising 2,702 positions recorded with 1° spatial resolution [8]; KEMAR is another, with 710 positions and 5° resolution [7]. For the individualized HRTFs, we selected 48 values in the database best corresponding anthropometrically to the study subjects (see below). The stimulus was noise with a band pass at 300–1200 Hz and 100 ms duration. Intensity was set at 65 dB HL (subject's reported comfort level) in each ear. The 4 types of HRTF were presented in random order in series comprising 0° (frontal plane), 50° (left lateral plane) and 180° (posterior plane) reference positions.

A second series of tests measured MAA monaurally, to assess spatial discrimination under simulated unilateral hearing loss. Sound intensity was reduced by 39 dB SPL in one headphone (left or right), with the other maintaining 60 dB. The reduction was equivalent to that achieved by associating earplugs in the outer ear plus earmuffs [9], and was either ipsilateral (MON-i) or contralateral (MON-c) to the lateral reference position.

To assess relations between individual anthropometric measurements and individualized HRTFs, 12 head and outer ear dimensions were compared to those associated with each of the 48 individualized HRTFs [6]. Best Match was calculated for each participant by identifying the smallest difference between the anthropometric measurements and those of the 48 individualized HRTFs. Two approaches were used for this, using either the combined 12 head and outer ear dimensions (Total Best Match: TBM) or just the 6 head dimensions (Partial Best Match: PBM). The idea of using the 2 approaches was to be able to specifically assess the role of the outer ear in spatial discrimination. As the 12 TBM anthropometric measurements included the outer ear, this HRTF dataset was presumed to provide more precise spatial simulation. MAA discrimination performance was assessed with the HRTFs for the best TBM correspondence in the 3 stimulation conditions: 1 binaural and 2 monaural. In all, participants' performance was tested in 6 conditions (binaural: KEMAR, KU100, TBM and PBM; monaural: TBM MON-c and TBM MON-i) for 3 spatial reference positions (0°, 50° and 180°).

For analysis, individual MAA values were averaged per group and per HRTF in the 3 reference positions. Normality was checked on Shapiro-Wilk test; MAA values were not normally distributed for KU100 at 180°, KEMAR at 50°, PBM at 50° and all monaural

Fig. 1. Box plot of MAA values at the 0° frontal reference position for the 4 HRTF databases. Circles show individual values; Xes show means; the asterisk indicates significant values ($P < 0.005$).

series. Homogeneity was checked on non-parametric Levene test, which showed homogeneous variance for the 3 reference positions ($P > 0.05$). Statistical analysis for repeated measures was then implemented on Rstudio software (lme4) using 2 factors (type of HRTF and spatial reference position) to assess the global effect of each factor, followed by multiple comparison on post-hoc test (multcomp package glht test) and comparison of mean MAA values for each HRTF at each position on non-parametric Wilcoxon test. The significance threshold was set at $P < 0.005$, with p-values between 0.05 and 0.005 considered suggestive [10].

3. Results

Statistical analysis for repeated measures revealed effects of both reference position [$X^2(2, n = 27) = 20.6$; $P < 0.001$] and type of HRTF [$X^2(3, n = 27) = 21.8$; $P < 0.001$], but with no significant interaction between the two [$X^2(6, n = 27) = 11.3$; $P = 0.078$].

3.1. Comparisons of types of prerecorded HRTF.

Fig. 1 shows MAA according to type of HRTF in the frontal plane (0°). Wilcoxon comparison of means showed that KU100 generated smaller MAAs than KEMAR in both frontal and lateral position; the difference was not significant, but there were suggestive differences ($P < 0.05$) with respect to the mean values for TBM and PBM in the frontal and lateral planes (see Table 1).

Post-hoc comparison of MAA according to reference position found significantly lower values at 0° than 50° ($t(26) = -3.69$; $P < 0.001$) or 180° ($t(26) = -4.14$; $P < 0.001$). Wilcoxon comparison of means showed that KU100 generated smaller MAAs at 0° than at 180° (95%CI, $[-8.96; -2.81]$; $P < 0.001$). The other types of HRTF showed no significant differences in MAA according to reference position.

3.2. Spatial discrimination in monaural condition

Fig. 2 shows MAA values in the binaural and monaural conditions for total individualized HRTF (TBM). Repeated measures analysis found MAA to vary with condition (monaural vs binaural) ($X^2(2, n = 27) = 41.17$; $P < 0.001$), but not with reference position ($X^2(2, n = 27) = 4.9$; $P = 0.083$). Wilcoxon test found significant differences between the binaural and monaural conditions in frontal position for MON-c ($16.4 \pm 10.5^\circ$; $P < 0.001$; 95%CI, $[-11.12; -5.18]$) and MON-i ($14.4 \pm 9.3^\circ$; $P = 0.001$; 95%CI, $[-10.2; -3.3]$), in lateral position for MON-c alone ($18^\circ \pm 8.4$; $P = 0.004$; 95%CI, $[-9.14; -2.1]$), and in posterior position for MON-

Table 1
MAA according to reference position and type of HRTF.

0°	Mean MAA per HRTF	P-value	95% CI
KU100 < Kemar	5.6° ± 7.3° VS 9.7° ± 8.3°	0.002*	[-7.12 to -1.49]
KU100 < PBM	5.6° ± 7.3° VS 7.9° ± 7.8°	0.035.	[-5.83 to -0.41]
		0.033.	[-5.05 to -0.33]
50°	Mean MAA per HRTF	P-value	95% CI
KU100 < Kemar	7.5° ± 6.4° VS 14.5° ± 9.3°	0.0001**	[-9.94 to -3.19]
KU100 < TBM	7.5° ± 6.4° VS 12.6° ± 8.4°	0.005.	[-7.37 to -2.12]
KU100 < PBM	7.5° ± 6.4° VS 10° ± 6.6°	0.028.	[-4.81 to -0.24]
180°	Mean MAA per HRTF	P-value	95% CI
TBM < KU100	9.7° ± 8.9° VS 12.1° ± 8.9°	0.222	[-3.66 to 1.56]
TBM < Kemar	9.7° ± 8.9° VS 14° ± 10.6°	0.026.	[1.36 to 4.64]
TBM < PBM	9.7° ± 8.9° VS 9.9° ± 9°	0.09	[-3.66 to 1.56]

Asterisks indicate significant values ($P < 0.005$), dots suggestive values ($0.05 < P < 0.005$).

Fig. 2. Box plot of MAA values in binaural and ipsi- and contra-lateral monaural simulation conditions for TBM. Circles are outliers; Xes show means; asterisks indicate significant values ($P < 0.005$).

c ($17.1° \pm 11.7°$; $P < 0.001$; 95%CI, [-10.04; -4.15]) and MON-i ($19.5° \pm 12.8°$; $P < 0.001$; 95%CI, [-13.44; 5.98]).

4. Discussion

The main aim of the present study was to assess the feasibility of a method of spatial discrimination evaluation using spatialized sound stimuli via headphones. This assessment could be included in general audiological work-up for spatial hearing alongside measurement of absolute location. Values in normal-hearing subjects were comparable to those reported in the literature for MAA in free field. Benneman et al. [4] found MAA varying from 6.9° in the 65° position to 7.2° in the 95° position. Likewise, Kühnle [5] found smaller MAA (5.3° at 0° and 7.7° at 60°) with low than high frequency stimuli (7° at 0° and 10.2° at 60°) [5]. In binaural condition, mean values for MAA via headphones were globally similar to those in free field on the KU100 mannequin ($5.6° \pm 7.3$ at 0° and $7.5° \pm 6.4$ at 50°) and slightly greater (by 3° and 5°) with individualized HRTFs ($8.3° \pm 7.2°$ at 0° and $12.6° \pm 8.4°$ at 50°). Values were sufficiently similar to those reported in free field for the headphone test to be used in clinical practice. The method allows MAA measurement with 2 reference positions (front and back) with less than 10 minutes' assessment time, making it particularly useful for spatial discrimination assessment in hearing-impaired patients as a complement to other location assessments.

The study objective was to identify the type of prerecorded HRTF giving MAA values closest to free-field findings. MAA values depended on type of HRTF and on reference position. In frontal and lateral position (0° and 50°), using HRTFs from the KU100 mannequin MAA values were smaller than with individ-

ualized HRTFs or the KEMAR mannequin, and were also closest to free-field values in normal-hearing subjects for 750 Hz pure tones [1] and 400 Hz clicks [11]. MAA showed progressive decrease in spatial discrimination from frontocentral to posterior position, as frequently reported in free field [6–8] and in studies using HRTFs [9]. Discrimination precision at 180° (posterior field) was poorer using the KU100 mannequin than individualized HRTFs (e.g., $9.7° \pm 8.9°$ for TBM vs $12.1° \pm 8.9°$ for KU100 at 180°). This was also reported by Bombhart and Wenzel [6], who suggested that individualized HRTFs better replicate the experience of free-field spatialization. Wenzel also highlighted the large inter-subject variation using non-individualized HRTFs (in the present case, KEMAR), with 19% anteroposterior confusion in free field, increasing to 31% via headphones [12]. This discordance may be because the anthropometric data in the individualized HRTF databank were not strictly comparable to those measured in the present subjects; we chose the nearest values, but the correspondence was not perfect.

The second aim was to measure MAA in a monaural condition simulating unilateral hearing loss, which impairs binaural integration and thus spatial discrimination. Angular discrimination was poorer in the monaural than the binaural condition, confirming the importance of analysis of interaural difference in spatial discrimination. These findings were in agreement with the literature regarding unilateral hearing loss. For example, Cai et al. [13] found much smaller mean MAA in normal-hearing subjects (4.8°) than in patients with asymmetric hearing loss (13.6° for left impairment, 10.3° for right impairment). Harris [14] reported 4.1° increase in free-field MAA binaurally versus 11.3° monaurally in normal-hearing subjects at 8,000 Hz.

MAA assessment in clinical practice could broaden the field of spatial auditory assessment, with information going beyond classical assessment of spatial location by including more cognitive aspects. The MAA task requires a judgment of similarity, involving cognitive mechanisms such as focused attention and short-term memory in addition to spatial competence as such; these factors are little involved in simple free-field spatial location tasks. MAA may thus be a better index of auditory spatial deficit in all its dimensions, including cognitive functions.

5. Conclusion

In the present study, spatial discrimination assessment by MAA via headphones using KU100 HRTFs was reliable and robust. In normal-hearing subjects, the assessment was reliable in anterior and lateral space, but less so in posterior space. Thus, the protocol of spatial discrimination based on HRTFs delivered via headphones is suited for rapid but precise clinical assessment of spatial hearing in patients, complementing classical acoustic location assessment.

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgments

The authors thank Kuzma Strelnikov, Louis Villejoubert and Léa Pasquio for help with the MAA assessment pilot study. The research received funding from the Clinical Research and Innovation Directorate of Purpan Hospital (University Hospital of Toulouse, France), the CNRS and ANR Audition 3D (ANR 16-CE17-0016).

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