



A Front-Back Confusion Metric in Horizontal Sound Localization: The FBC Score

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ABSTRACT

In sound localization experiments, currently used metrics for front-back confusion (FBC) analysis weight the occurring FBCs equally, regardless of their deviation from the cone of confusion. To overcome this limitation, we introduce the FBC Score. A sound localization experiment in the horizontal plane with 12 bilaterally implanted cochlear implants (CI) users and 12 normal hearing subjects was performed to validate the method with real data. The overall FBC Rate of the CI users was twice as high as the FBC Score. For the control group, the FBC Rate was 4 times higher than the FBC Score. The results indicate that the FBC Rate is inflated by FBCs that show a considerable deviation from the corresponding value on the cone of confusion.

CCS CONCEPTS

• **Human-centered computing** → **Laboratory experiments; Virtual reality.**

KEYWORDS

cone of confusion, virtual audio, binaural cues, head related transfer function, spatial hearing outcome measures, cochlear implants

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1 INTRODUCTION

Sound source localization primarily relies on the evaluation of interaural time and level differences [Blauert 1997; Rayleigh 1907]. Front-back confusions (FBCs) occur because sound sources on the cone of confusion are equidistant from the left ear and equidistant from the right ear and thus provide identical interaural time and level differences for a listener [Rayleigh 1907]. An illustration for a sound source on the cone of confusion is given in Figure 1.

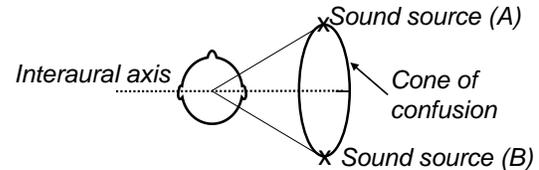


Figure 1: The cone of confusion is defined as an imaginary cone extending outward from the center of the head [Wallach 1938]. The axis of the cone is defined by the interaural axis. Due to the symmetry of this cone around the interaural axis, sound source (A) and (B) produce identical interaural time and level differences. Sound sources on the cone of confusion are thus useless for binaural sound localization.

It has been noted that FBCs occur frequently when sounds are virtually spatialized using individualized, head-related transfer functions (HRTFs) [Morimoto and Aokata 1984; Wightman and Kistler 1989]. By using non-individualized HRTFs, as in virtual reality/audio systems [Iida 2019; Steadman et al. 2019] or hearing aid audio processors [Akeroyd 2014], this negative influence of FBCs on the sound localization ability is further increased [Wenzel et al. 1993]. The analysis of FBCs thus provides important information about the extent to which HRTFs or microphone directionality approximate a normal spatial hearing experience.

FBC errors are not simply outliers with extreme error amplitudes. The underlying cause is different from normal localization errors (see Figure 1) which is why FBCs should be analyzed separately [Carlile et al. 1997; Fischer et al. 2020a; Hill et al. 2000; Langendijk et al. 2001; Pastore et al. 2018; Wightman and Kistler 1999].

There is a continuing debate in the literature on the definition of an FBC error. In horizontal sound localization experiments, the most common definition classifies responses crossing the interaural axis as FBCs [Cai et al. 2018; Carlile et al. 1997; Hill et al. 2000; Langendijk et al. 2001; Wightman and Kistler 1999; Zahorik et al. 2006]. This definition, which defines the FBC Rate, is sufficient for experiments that only require a coarse angular resolution of the test setup or feedback method [Montagne and Zhou 2018; Pastore et al. 2018; Wimmer et al. 2017]. However, such setups do not reflect virtual audio scenarios with arbitrary sound source configurations and also limit the measurement resolution for sound localization accuracy.

A refined FBC definition requires FBC responses to fall within a specific range of a response-dependent regression line, which

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is mirrored on the interaural axis [Macpherson and Middlebrooks 2000; Montagne and Zhou 2018].

Further definitions as to what constitutes a FBC error are defined by fixed threshold values. These thresholds refer either to a minimum required deviation of the given response in relation to the interaural axis or to a maximum allowed deviation between the response and the stimulus mirrored on the interaural axis [Letowski and Letowski 2011]. There is no general consensus regarding the magnitude of the thresholds.

Apart from thresholds that are not standardized, the current limitation of FBC analysis approaches is that all FBCs are considered equally strong. The deviation from the measurement position to which the error refers, which is the deviation of the response from the stimulus position mirrored on the interaural axis, is not considered. Errors, such as right-left confusions [Majdak et al. 2011], inflate the FBC Rate and may lead to wrong conclusions about the outcome. In addition, special care should be taken with stimuli presenting close to the interaural axis, as localization errors overlap with FBC errors in this area.

Herein, we propose a metric that allows to quantify the impact of FBCs on sound localization outcomes in the horizontal plane more precise than with the commonly used FBC Rate. The FBC Score can be applied regardless of the number of available localization results, the localization performance of the subjects and the measurement setup.

2 MATERIALS AND METHODS

2.1 Study design and participants

This study was designed in accordance with the Declaration of Helsinki and was approved by the local institutional review board (KEK-BE, No. 2018-00901). Twelve bilaterally implanted cochlear implants (CIs) users participated in the study, all using Sonnet (Med-El GmbH, Innsbruck, Austria) processors with an omnidirectional microphone setting. The CI users had a monosyllabic word recognition score in quiet of 70 % or better at 60/65 dB SPL. For comparison, a control group of 12 normal hearing (NH) adults was included.

2.2 Static Sound Source Localization Test

Static sound source localization was performed with 12 equally spaced loudspeakers arranged in a circle around the subject (at $0^\circ, 30^\circ, \dots, 330^\circ$). The test stimulus consisted of pink noise with 200 ms length. To prevent the use of monaural level cues, level roving between 60 to 70 dB SPL was applied. In total, 36 stimuli per subject were played, 3 stimuli per loudspeaker [Fischer et al. 2020b]. The order of the stimuli with respect to the loudspeaker was randomized [Wimmer et al. 2017]. The loudspeakers were hidden behind a sound transparent curtain, no prior knowledge about possible stimuli directions was provided to the subjects [Fischer et al. 2020a]. The subjects' feedback on the perceived location of the stimulus was recorded via a graphical user interface showing a dial with a resolution scale of 1-degree angle and a login button.

2.3 Calculation of the FBC Score

We define the outcome of a sound localization experiment as a set of stimuli $\hat{S} = \{\hat{s}_1, \hat{s}_2, \dots, \hat{s}_{\hat{N}}\}$ and corresponding subject responses

$\hat{R} = \{\hat{r}_1, \hat{r}_2, \dots, \hat{r}_{\hat{N}}\}$, where \hat{N} denotes the total number of test stimuli. In relation to the FBC Rate (see Eq. 1), only responses that do cross the interaural axis are considered for the FBC analysis. After exclusion of the responses that do not cross the interaural axis, we obtain a reduced set of stimuli $S = \{s_1, s_2, \dots, s_N\}$ and responses $R = \{r_1, r_2, \dots, r_N\}$ with N stimuli or responses.

$$\text{FBC}_{\text{RATE}} = \frac{N}{\hat{N}} \cdot 100 \quad (1)$$

The ideal position of an FBC, i.e., the position of a stimulus s_i mirrored on the interaural axis, is defined as the FBC center c_i . We compute the deviation θ_i between the response r_i and the FBC center c_i as the shortest absolute angular difference (minor arc). An example for one stimulus-response pair is given in Figure 2. The maximum allowable deviation $\theta_{\max,i}$ is defined by the interaural axis and the FBC center c_i (see Figure 3). The farther away a response r_i is from its corresponding FBC center and the closer to the interaural axis, the less likely it is to be an FBC. Therefore, we introduce a weighting factor w_i for each measured FBC:

$$w_i = 1 - \frac{\theta_i}{\theta_{\max,i}} \quad (2)$$

where $\theta_{\max,i}$ is the maximum deviation in the direction of the response (clockwise or counterclockwise) under consideration of the interaural axis. The weighting w_i ranges from 0 (response on the interaural axis) to 1 (a perfect FBC). An illustration of the procedure is given in Figure 3.

To provide a subject-level FBC metric that considers deviations of the responses from the cone of confusion and their proximity to the interaural axis, we propose the FBC Score as defined in Equation 3.

$$\text{FBC}_{\text{SCORE}} = \text{FBC}_{\text{RATE}} \cdot \frac{1}{N} \sum_{i=1}^N w_i \quad (3)$$

An FBC Score of 100 % indicates that all responses were FBCs and exactly match the stimulus positions mirrored on the interaural axis. In contrast, an FBC Score of 0 % would indicate that the responses did not contain any FBCs during the trial. For a calculation example with numeric data, a step-by-step guide for the calculation of the FBC Score with corresponding explanations is provided in the Appendix A. To facilitate the calculations, we implemented the procedure as a MATLAB function¹. The function takes the sets of stimuli \hat{S} and responses \hat{R} as input parameters. In addition to the calculations described above, a separate analysis of front-back and back-front confusions is performed.

3 RESULTS

Table 1 shows the results of the FBC Score analysis compared to the FBC Rate for each CI user and NH subject. For the CI users, the mean overall FBC Score is 27 % in contrast to the almost twice as high mean FBC Rate of 47 % ($p < .001$, two-sided Wilcoxon signed rank test). The Wilcoxon signed-rank test was applied because it does not assume normality in the data. It allows to compare two sets of scores, that come from the same participants.

¹https://www.artorg.unibe.ch/research/hrl/data/fbc_score/

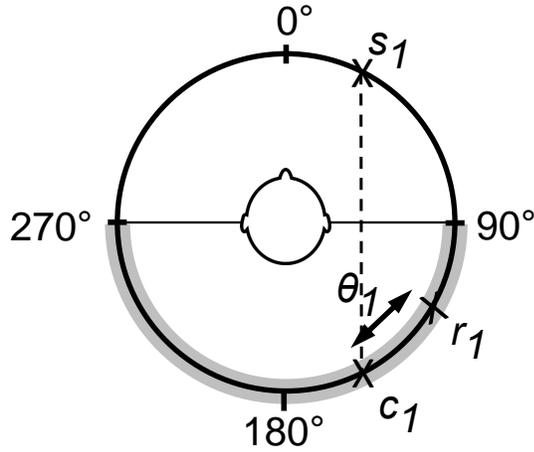


Figure 2: The FBC center c_1 is the stimulus origin s_1 mirrored on the interaural axis. The interaural axis corresponds to the line from 270° to 90° . Valid FBCs can occur within the light shaded stripe. The deviation of the response r_1 from c_1 is denoted with θ_1 . In this example, the response r_1 lies in counter clockwise direction with respect to c_1 .

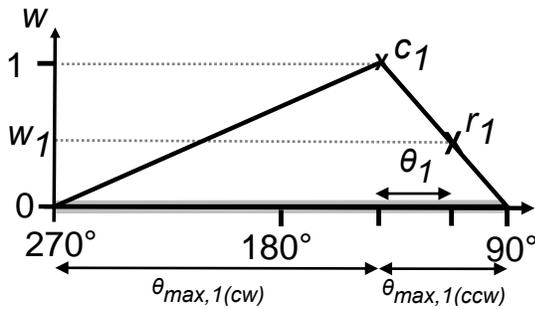


Figure 3: Weighting factor calculation for the example shown in Figure 2. The y-axis shows the front-back confusion weighting factor w and the x-axis shows the rear azimuth. The deviation of the response r_1 from c_1 is denoted by θ_1 . The response r_1 lies in counter clockwise (ccw) direction with respect to s_1 , therefore $\theta_{\max,1}$ is equal to $\theta_{\max,1(ccw)}$. The areas $\theta_{\max,1(ccw)}$ and $\theta_{\max,1(cw)}$ are limited by the interaural axis as defined in Figure 2.

For the NH control group, the FBC Rate is 4 times as high as the FBC Score (FBC Score: 1 %, FBC Rate: 4 %; $p=0.063$).

4 CONCLUSION AND DISCUSSION

For the evaluation of sound localization experiments, the errors are quantified in terms of their deviation from the stimulus position. However, for FBC analysis, thus far, only a rough distinction between "no FBC" and "FBC" is made, and the occurrences are counted. In this report, we propose a method for quantifying the severity of an FBC, allowing a more specific analysis of this phenomenon.

Table 1: The table shows the results on subject-level for the front-back confusion (FBC) score analysis compared to the FBC Rate for each cochlear implant (CI) user and normal hearing (NH) subject. Furthermore, an overview of the demography of the participants is given.

ID	FBC Rate (%)	FBC Score (%)	Age (yr.)	CI experience (Left/Right, in yr.)
CI01	60.0	41.3	20	5/17
CI02	46.7	19.8	67	16/15
CI03	53.3	28.8	48	8/9
CI04	50.0	39.9	62	6/1
CI05	46.7	22.7	64	12/13
CI06	43.3	26.9	66	19/17
CI07	40.0	20.1	25	17/13
CI08	46.7	18.2	44	12/6
CI09	33.3	15.4	58	3/6
CI10	50.0	31.3	57	12/14
CI11	40.0	23.4	62	7/1
CI12	50.0	27.8	22	4/3
NH01	0.0	0.0	32	n.a.
NH02	0.0	0.0	55	n.a.
NH03	0.0	0.0	26	n.a.
NH04	0.0	0.0	41	n.a.
NH05	10.0	4.2	43	n.a.
NH06	6.7	0.0	26	n.a.
NH07	16.7	9.4	45	n.a.
NH08	0.0	0.0	25	n.a.
NH09	6.7	1.3	29	n.a.
NH10	0.0	0.0	31	n.a.
NH11	0.0	0.0	28	n.a.
NH12	3.3	0.0	37	n.a.

In the example presented here, the FBC Rate of the CI users would indicate that the tested subjects are prone to FBCs (47 %). However, the FBC Score shows that this assumption does not necessarily hold true since the impact of the FBCs is significantly smaller by a factor of 1.7 (27 %). Therefore, the FBC Rate in our example includes many FBCs with a considerable deviation from the corresponding stimulus position on the cone of confusion, to which this phenomenon actually refers.

A critical examination of the FBC Score could raise the question of whether the calculated score is interpretable and unambiguous. Indeed, an FBC Score value near 0 % could indicate either no FBCs or many FBCs combined with wide scatter of lateral angle judgements. In both scenarios, the FBC Score must ensure that FBCs play no role in the analysis of the subject's spatial hearing characteristics. The first scenario is trivial, the value equals the result obtained with the FBC Rate. The assumption for the second scenario would be that all localization responses of the subject are found at a very small distance from the interaural axis. An extreme example for this this scenario would be, that all stimuli are played frontally from 0° and answered by the subject constantly at 90.1° . This scenario would result in an FBC Rate of 100 %. The FBC Rate would also be 100 % for right-left confusions [Majdak et al. 2011], for example when all stimuli are played from 90.1° position and the subject answers constantly at 270.1° position. In both scenarios, the FBC Rate is deceptive, since the underlying errors are most likely not 100 % due to FBCs. The FBC Score intercepts the fallacy of the FBC Rate according to its calculation rule and shows a slightly higher value than 0 %.

In contrast to a subject who is not susceptible to the FBC error type (FBC Score = 0 %), an FBC Score value near 100 % shows the highest possible susceptibility of a subject to FBCs. All responses of the subjects were FBCs and exactly match the stimulus positions mirrored on the interaural axis. As illustrated above, the FBC Rate does not reflect the underlying cause of FBCs as accurate as the FBC Score, because an FBC Rate value of 100 % does not necessarily indicate a high susceptibility of the subject to FBCs. For any value of the FBC Score, the following applies: FBC Score \leq FBC Rate. Compared to the FBC Rate, the FBC Score is not so strongly affected by error types that may not be due to FBCs.

In the above section we have shown that although the emergence of an FBC Score value is multicausal, the metric does serve its purpose. It performs a weighting of localization errors that allows to assess the subject's susceptibility to the FBC error type more specifically than with the FBC Rate. An alternative option to illustrate the subjects' susceptibility on the phenomenon of FBCs would be to indicate, in addition to the FBC Rate, the localization error with respect to the stimulus' position mirrored on the interaural axis. In our opinion, however, this approach may overestimate the importance of FBCs caused by stimuli near the interaural axis for two reasons: First, the influence of FBCs near the interaural axis is rather small in real life situations. Second, both error types, i.e., the FBC and localization errors, overlap for stimuli originating from close to the interaural axis, which can lead to distortions in the FBC analysis. By weighting the distance between the stimulus and the interaural axis and by considering the proximity of the response to the interaural axis, this influence on the assessment of the FBC phenomenon can be mitigated with the FBC Score. The effect of this weighting is particularly demonstrated by the 4 times lower FBC Score compared to the FBC Rate in the NH control group. Here, all FBC-causing stimuli originated from the measurement position with the smallest distance to the interaural axis.

The studies in [Macpherson and Middlebrooks 2000; Montagne and Zhou 2018] defined responses as FBCs if the maximum deviation from the FBC center was less than or equal to a 40 or 45-degree angle. Such a static threshold value is not feasible in virtual environments with non-individualized HRTFs or in clinical studies with hearing-impaired subjects, due to the large differences in the inter-subject localization accuracy [Akeroyd 2014; Steadman et al. 2019]. An explanation of the underlying theoretical and psychoacoustic mechanism would be missing for the justification of such a threshold value. Besides the static threshold value, the iterative regression method applied in [Macpherson and Middlebrooks 2000; Montagne and Zhou 2018] relies on the distribution and number of sound localization responses. The FBC Score does neither depend on a predefined threshold value nor on the quality or quantity of the localization results. This may be especially important when evaluating the performance of hearing-impaired subjects in clinical trials. These localization results often show a wide individual variability [Akeroyd 2014] and consist of limited samples due to the limited testing time and subject attention. In addition to evaluate the performance of hearing-impaired subjects, the FBC Score may also be used to evaluate the quality of sound spatialization of a virtual reality system [Steadman et al. 2019].

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Table 2: Data of the calculation example.

Test item	Stimulus ($^{\circ}$) direction s_i	Response ($^{\circ}$) direction r_i	FBC center ($^{\circ}$) c_i	Deviation ($^{\circ}$) θ_i	Maximum ($^{\circ}$) deviation $\theta_{\max,i}$	Weighting factor w_i
1	20	200	160	40	110	0.64
2	280	260	260	0	10	1.00
3	65	95	115	20	25	0.20
4	350	120	190	70	100	0.30

A EXAMPLE CALCULATION OF THE FBC SCORE WITH NUMERIC DATA

In the following, we illustrate the calculation of the FBC Score using a small example data set with 5 stimuli \hat{S} and responses \hat{R} from a sound localization test in the horizontal plane (see Figure 4). Table 2 summarizes the results for the computational steps involved.

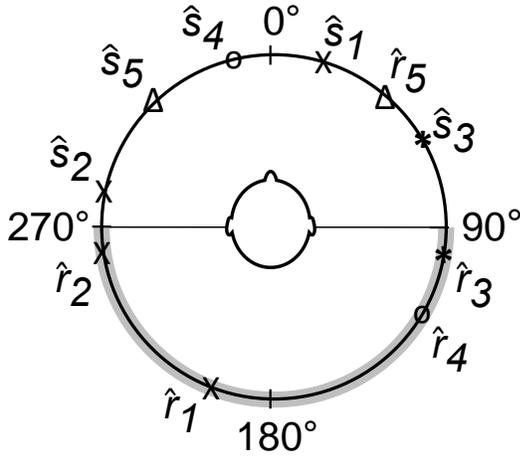


Figure 4: Visualization of the data for the example calculation of the front-back confusion (FBC) Score. Stimuli are indicated with \hat{S} and responses with \hat{R} . In this example, all stimuli lie inside the frontal azimuth and thus responses inside rear azimuth (light shaded area) are considered FBCs.

$$\hat{S} = \{\hat{s}_1 = 20^{\circ}, \hat{s}_2 = 280^{\circ}, \hat{s}_3 = 65^{\circ}, \hat{s}_4 = 350^{\circ}, \hat{s}_5 = 315^{\circ}\}$$

$$\hat{R} = \{\hat{r}_1 = 200^{\circ}, \hat{r}_2 = 260^{\circ}, \hat{r}_3 = 95^{\circ}, \hat{r}_4 = 120^{\circ}, \hat{r}_5 = 40^{\circ}\}$$

Step 1 - Calculate the FBC Rate:

First, the FBC Rate is calculated. It is defined as the rate of the number of responses crossing the interaural axis with respect to the number of presented stimuli (see Eq. 1). Only \hat{r}_5 does not cross the interaural axis. Excluding \hat{s}_5 and \hat{r}_5 results in $N = 4$ pairs of stimuli s_i and responses r_i and an FBC Rate of 80 %.

Step 2 - Calculation of c_i and θ_i :

The FBC center c_i is obtained by mirroring the stimulus position s_i on the interaural axis. The deviation θ_i is calculated as the absolute difference between the response r_i and c_i measured over the minor arc. For example, for stimulus 3, we have $\theta_3 = |r_3 - c_3| = |95^{\circ} - 115^{\circ}| = 20^{\circ}$.

Step 3 - Calculation of $\theta_{\max,i}$:

The maximum deviation $\theta_{\max,i}$ between r_i and c_i is limited by the interaural axis. If r_i lies in clockwise direction of c_i , the clockwise limit is applied ($\theta_{\max,i} = \theta_{\max,i(cw)}$). The same applies for the counter clockwise direction.

For example, with stimulus s_3 , the minor arc for the response r_3 lies in counter clockwise direction to the FBC center c_3 , therefore the maximum deviation is $\theta_{\max,3} = \theta_{\max,3(ccw)} = 25^{\circ}$.

Step 4 - Calculation of w_i :

With θ_i and $\theta_{\max,i}$ we compute the weighting factor w_i for each stimulus using equation (2).

Step 5 - FBC Score:

We now calculate the FBC Score as defined in Equation (3):

$$\text{FBC}_{\text{SCORE}} = 80\% \cdot \frac{0.64+1.00+0.20+0.30}{4} = 42.8\%$$

To facilitate the calculations, we implemented the procedure as a MATLAB function¹.