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THEORY OF THE REFLECTIVE LOCALIZATION OF SOUND SOURCES

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In order to explain the mechanism of distance localization of sound sources with hearing, a hypothesis was stated that a "*situation analyzer*" exists in the man central nervous system. The analyzer is capable of perceiving not only the direction of direct and reflected sounds reaching the listener, but also the position of reflecting surfaces, distance of the reflection points and corresponding angles, for the so-called early reflected sounds.

On the basis of the above mentioned hypothesis, and considering certain acoustic situations and some visual analogies, foundations for a new theory of the reflective localization of sound sources have been created. Suggestions important for the psychoacoustics in general as well as for room – acoustics and studio – technique applications have been outlined.

1. Introduction

The ability of sound source localization is an important property of the sense of audition. Binaural audition allows the precise localization of the direction of a sound source in the space surrounding the listener with an angular inaccuracy below 1° to 20°, depending on the position of the source in respect to the listeners head. It also allows the estimation of the distance between the sound source and listener in rooms with walls reflecting sounds, with a good accuracy.

The mechanism of stereophonic audition is based on the properties of binaural hearing. With the application of a pair of spaced loudspeakers supplied with adequate signals apparent sources are formed, which are localized in the sound image similarily as the real sources, although generally with lower accuracy. Stereophonic hearing is of great practical importance to the technique of stereophonic systems. That is why there is a wide and constant interest in the theories of directional hearing, manifested by many publications concerned with this subject. For example, in BLAUERT'S monography [5] over six hundred papers concerned partially and in the whole with directional hearing, have been mentioned.

2. Former theories

The two oldest theories of the directional source localization are: the theory of the differences of the sound intensity on the entry to the left and right ear, and the theory of differences of signal access times to the left and right ear; both coming from RAYLEIGH, from the years 1877 and 1907.

A series of later theories is in reality only complements and expansions of the intensity and phase theories, which with these complements exist up to now, describing two parallely acting mechanisms of the source directional localization with the aid of audition. Mentioning here all individual theories, presented in detail in the literature [4] – [7], [9], would occupy too much place.

It should be noticed, that although the mechanism of the directional localization was thoroughly investigated theoretically and certain details were determined as goals of further research, the mechanism of the distance localization was not explained. Though there are several theories of the distance localization, still none of them explains the localization inaccuracies reaching up to about ten to twenty per cent.

The accessible in literature experimental data concerning the thresholds of directional localization in specific research situations, come mostly from experiments conducted under a free acoustical field conditions, e. g., in an anechoic chamber or in an artificially modelled field. These experiments are not fully competent in relation to the real conditions, especially in the view of the influence of reflected sounds on the localization mechanism.

3. Theory of reflective localization

The *law of the first wave front* formulated by CREMER in 1948, or the *precedence effect*, so-called by WALLACH in 1949, soon found a practical confirmation in experiments conducted by HAAS and drove the attention away from the influence of reflected sounds on source localization. For it was generally acknowledged, that only the direct sound from the source was the signal, which makes subjective localization possible, blocking at the same time out the sensitivity of the localization mechanism to following reflected sounds coming from this source during the time of the HAAS constant, that is about 20–50 ms.

However, cases of a lack of blocking in the time range of the HAAS constant were soon stated [8]. Informations appeared about a better localization ability in rooms with reflecting walls, than in rooms with completely absorbing walls. Similar observations were made especially in the 60-ties in the course of determining the ability of directional localization of sound sources under water. This was done by free divers in not silenced pools [3]. It was found, that the threshold of angular localization, equalling about 10° in a highly damped, almost anechoic pool, decreased to about 5° for experiments in a pool with well reflecting walls.

The above mentioned informations showed the possible share of reflected sounds in the localization mechanism, however, they were not applied to generalizations. Lately, BENADE [2] drew attention to the fact, that the sequences of first reflections, reaching the listener in a room, some how increase his ability of localizing sound sources.

Auditory localization of sources in a half-open space e. g. in two street situations can easily convince us of the influence of reflections. The first situation is, when the street surfaces and objects in the street are not attenuated, and the second one when the same street covered with a thick layer of freshly fallen, fluffy snow. Source localization in a snow covered street is distinctly more difficult, just because for the lack of reflected sound.

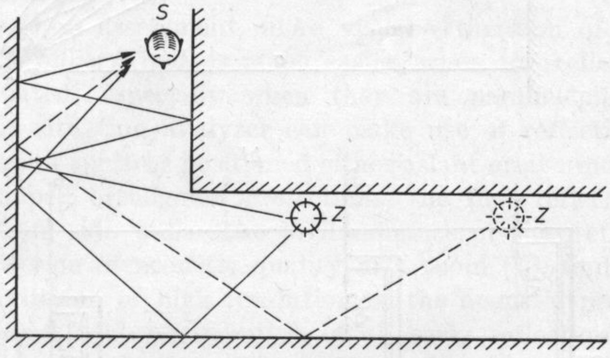

Fig. 1. Localization example without any application of a direct sound

The results of considerations of cases, where the direct sound does not reach the listener at all, are an argument against the theory, stating that the first front of a direct sound has a decisive importance for localization. A *L*-shaped corridor can be an example (Fig. 1). No direct sound, or single reflected sound reaches the listener *S*. However, as experiments show, the listener correctly localizes the moving source of sound emitted by a person moving in the corridor. So, the sounds reflected from walls two, three and may be more times and then reaching the listener from different directions, are responsible for the subrequent localizations.

Therefore a hypothesis can be made, that the above mentioned blocking mechanism does not exist and that reflected sounds have a contribution in the localization mechanism. This hypothesis will not be contradictory to the law of the first wave front, if we assume that the sensory situation analyzer localizes not only the direction of the first and any following wave reaching the listener, but also it determines every time the position of the source on the basis of earlier perceived positions of the reflecting surfaces and the current evaluation of the directions from the point of reflection to the source (Fig. 2).

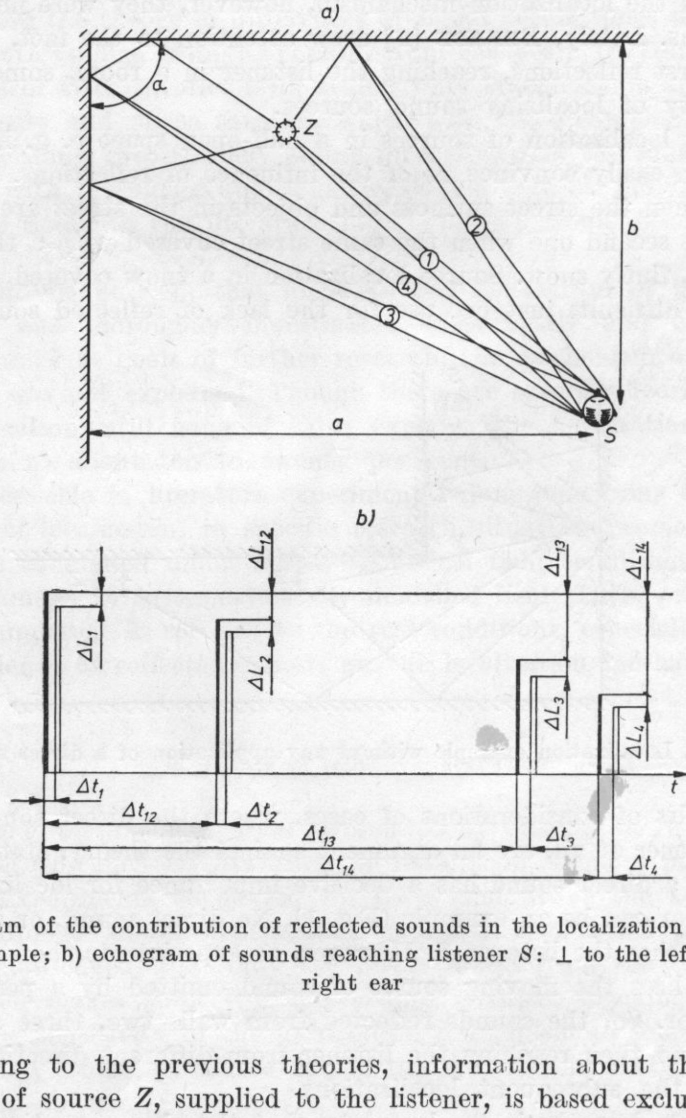

Fig. 2. Diagram of the contribution of reflected sounds in the localization of source Z: a) situation example; b) echogram of sounds reaching listener S: ⊥ to the left ear, ⫫ to the right ear

According to the previous theories, information about the directional localization of source Z, supplied to the listener, is based exclusively on the binaural difference, Δt_1 and ΔL_1. Meanwhile the information concerning the complete localization of source Z, supplied to the situation analyzer of the listener, according to the reflective theory, consists of a set of values of the main delays and attenuations of reflections: Δt_{12}, ΔL_{12}, Δt_{13}, ΔL_{13}, Δt_{14}, ΔL_{14}, the binaural values fo delays and attenuations: Δt_1, ΔL_1, Δt_2, ΔL_2, Δt_3, ΔL_3, Δt_4, ΔL_4, and the earlier perceived distances to walls a, b and their angle α.

The assumption, that the positions of reflecting surfaces and objects are perceived earlier is obvious, because the room in which the localization is conducted is usually *"aurally known"*, and mostly also known visually by the listener. This facilitates the estimation of the direction from point of reflection to the source. It should be presumed, that the mentioned here *"situation analyzer"* acts like a unit of the central nervous system, common to all man's senses. The work efficiency of the analyzer, working on the basis of the perceived acoustical signals, can be indirectly estimated, taking into account the localization accuracy of obstacles attained by blind.

The results of source localization on the basis of the first wave are compared in the situation analyzer with the localization results obtained on the basis of subsequent reflections, what increases the localization accuracy. The different directions of reflected waves, especiatly being at right angles to each other provides for the increase of the localization accuracy, due to the trigonometric relationships.

The aural direction assessment, alike visual estimation of the direction of reflections, e. g., billiard ball, is much easier, when the reflecting surfaces are regularily situated, especially when they are parallelepipedly shaped. In such a case the situation analyzer can make use of reflections of higher order, than in a case of surfaces positioned either aslant or at random. In rooms parallelepipedly shaped orthogonal projections, the first reflections come in the greater part from side walls. The predominance of side reflections, treated lately as a criterion of acoustic quality of a room [1], finds here an explanation as the criterion of high resolution of the acoustic perspective.

The assumption of the contribution of all early reflections in the process of sound source localization, that is the nonexistance of the reflection blocade, forces us to interpret the HAAS constant in a new way. Previously it was approximated at 20 to 50 ms, but practically it has a greater dispersion of values. According to the theory of reflective localization, the Haas constant finds a simple interpretation. It is the time in which the situation analyzer is still able to use the results of the analyzis of the reaching it reflected waves as informations on source localization. Waves reaching the situation analyzer after a longer period of time mostly after multiple reflections, are too difficult to analyze and do not give information on source localization. Subsequent waves do not improve the localization and give an impression of a reverberant sound without discrete localization.

The quantity of subsequent wave reflections which the auditory analyzer is able to reproduce and utilize is limited great. For a typical value of the HAAS constant $T_H \cong 50$ ms assuming the mean free path in the room to be equal to $d_m \cong 8.5$ m, the analyzer is able to utilize waves reflected n times, where

$$n = \frac{T_H c}{d_m} = \frac{50 \cdot 10^{-3} \cdot 340}{8.5} \cong 2.$$

Therefore in cases concerning typical rooms, waves giving information about the localization, are reflected once, or twice at the very most.

It is worth noticing, that the localized sources are either stationary or slowly moving. Thus the situation analyzer can take advantage of the localizations registered in earlier analysis.

The contribution of all early reflections in the localization process corresponds quite naturally to their share in the subjective integration of the loudness impression which in general lasts up to several, tens, or even hundred, miliseconds.

4. Optical analogies

In the course of examining possibilities of subconscious evaluation of the direction of reflections, visual analogies have to be considered. With the application of a mirror a person localizes seen objects not in the direction of sight, i. e., behind the minor, but in their real direction, determined on the basis of other observations. It is generally known, how precisely the direction and in consequence – the distance can be evaluated by a car driver using a rear-view mirror, or by a bus driver using single and dual mirrors. The "*acquaintance*" with the position of the mirror is a condition for a correct evaluation; what is an analogy to the initial "*sound familiarization*" with the room.

An increase of the localization accuracy by sight is obtained by superimposing results of the optical localization of the object, obtained from multiple path observations with the application of mirrors, shadows, cameras with picture monitors, etc. Analogously sound sources can be localized by hearing an improved accuracy due to well reflecting surfaces in a rectangle room without a roof.

5. Reflections and distance localization

"*Little is known, as far, about the mechanism of distance localization*" POTTER and STEINBERG wrote in the 50-ties in the introduction to a paper which dealt with the properties of audition [10].

Also not too much was explained in the further period of time.

Meanwhile the reflection mechanism of directional localization (described in p. 3) at the same time acts as a mechanism of distance localization due to simple trigonometric dependencies. In order to examine the quantity of the incremental sensitivity threshold of distance localization, resulting from this mechanism, the typical value φ for the incremental sensitivity threshold of angular localization in a horizontal plane passing through the ears of the

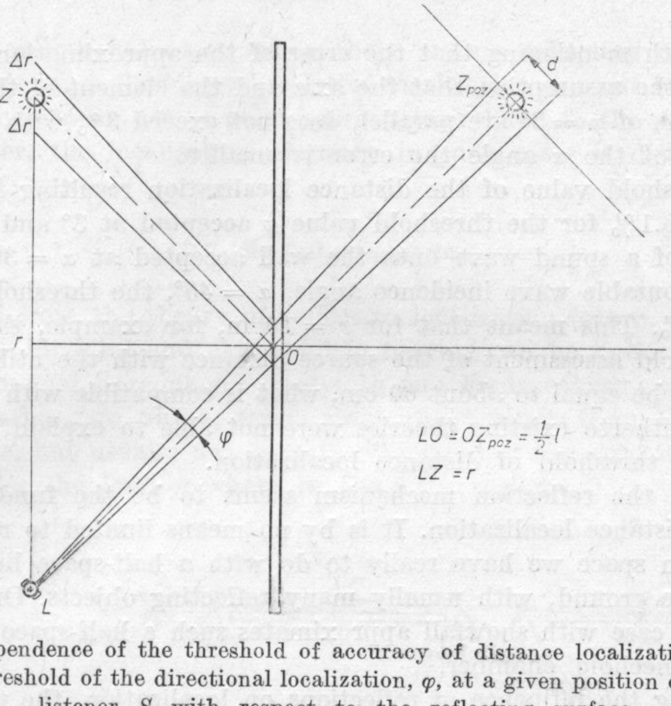

Fig. 3. The dependence of the threshold of accuracy of distance localization, Δr, on the value of the threshold of the directional localization, φ, at a given position of source Z and listener S with respect to the reflecting surface

listener has to be taken into account. For a straight ahead direction, φ equals about 3°, assuming that the listener turns his head, as it is in reality.

The neccessary trigonometric dependencies can be easily determined with the application of an apparent source Z_{poz} in a situation (Fig. 3), where source Z and the listener, at a distance r from it, are located near the reflecting plane, onto which a wave incides under an angle α.

$$\frac{1}{2}r = \frac{l}{2}\sin\alpha, \tag{5.1}$$

$$d = l\,\mathrm{tg}\frac{\varphi}{2}, \tag{5.2}$$

$$\Delta r \cong \frac{d}{\cos\alpha}. \tag{5.3}$$

From equations (5.1)–(5.3) it results that

$$\frac{\Delta r}{r} \cong 2 \frac{\operatorname{tg} \frac{\varphi}{2}}{\sin 2\alpha}. \tag{5.4}$$

It is worth mentioning that the error of the approximation in (5.3), resulting from the assumption that the axis and the element of the cone, with the apex angle of $\varphi = 3°$ are parallel, does not exceed 3 % with $\alpha = 45°$. For other values of the α angle the error is smaller.

The threshold value of the distance localization resulting from formula (5.4), equals 6.1 % for the threshold value φ accepted at 3° and for the incidence angle of a sound wave onto the wall accepted at $\alpha = 30°$. While for the most favourable wave incidence angle, $\alpha = 45°$, the threshold value equals only 5.2 %. This means that for $r = 10$ m, for example, the inaccuracy of the threshold assessment of the source distance with the utilization of reflections, will be equal to about 60 cm, what is compatible with practical observations. Hitherto existing theories were not able to explain this value of the accuracy threshold of distance localization.

Therfore, the reflection mechanism seems to be the fundamental mechanism of distance localization. It is by no means limited to rooms. In the so-called open space we have really to do with a half-space limited by the surface of the ground, with usually many reflecting objects. Only the mentioned above case with snowfall approximates such a half-space to a case of an almost anechoic chamber.

Discussing the influence of reflections on localization, the role of reflections has to be mentioned in the precise distance localization mechanism which functions not only with sea mammals and bats, but also with blind people.

6. Relative localization

Until now in discussions on directional hearing in literature and in experiments, a polar coordinate system with the begining at the point of the head of the listener, was generally used. Meanwhile man projects the surroundings by means of his senses in a local cartesian coordinate system rather, related to characteristic reflecting objects in these surroundings. He chooses instinctively the best directions of the main axes for such a system. This is the reason for man's predilection for rectangular rooms, which facilitate the localization of inside objects by the means of sight and hearing.

In the mentioned local system the relative localization takes place. It consists in determining the position of the source in relation to objects localized before, when the current position of his head in this system is known to the listener beforehand. Relative localization was surely developed in the course of the species evolution in order to compensate the mobility of the observer in the surroundings, especially of his eyes and ears, in relation to the objects and localized sources. Current localizations, remembered impressions and earlier general experiences of the observer form the image of the surroundings.

Only in exceptional cases, when there are no reflecting objects in the surroundings (e. g., a flat desert), relative localization can not be applied and we are forced to make use of polar coordinates related to the position of our head. However, the localization accuracy in such cases is distinctly lower.

7. Stereophonic hearing

It results from the theory of reflective localization (see p. 3), that localization in the binaural and stereophonic hearing can be uniformly interpreted. A two-channel stereophony base with two loudspeakers gives the possibility of radiating two waves, which reach the listener from the loud speakers directions, but usually not form the direction of the apparent source occuring between the loud speakers in the base region.

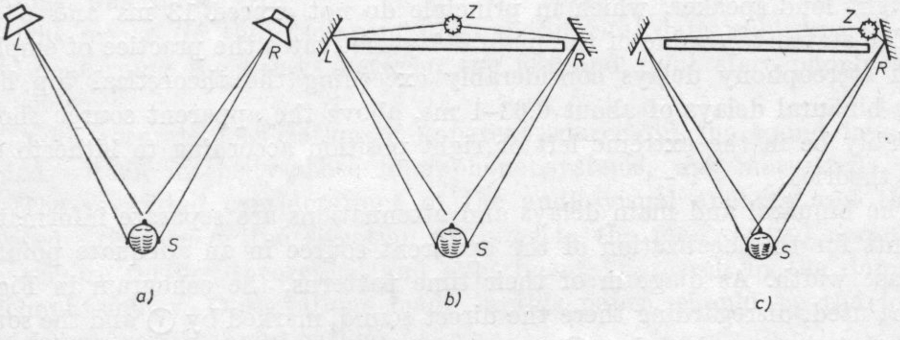

Fig. 4. Diagram of stereophonic hearing, taking into account the theory of reflective localization: a) audio monitoring system; b) equivalent system with a midpositioned source in the centre of the base; c) as above, but with the source in a side position

The two waves from the loud speakers, which reach the listener (Fig. 4a), can be treated as waves travelling from a real source located in place of an apparent source, reaching the listener after being reflected in the spots in which the loud-speakers are located (Fig. 4b). In the above reasoning an assumption was made that the listener is not reached by any direct wave from the source, just as if the base would be an insulating baffle. The midposition of an apparent source corresponds to a simultaneous attainment of the listener by both reflected waves (Fig. 4b). Whereas, an extreme side position of the apparent source (Fig. 4c), means that the left wave will reach the listener with a delay resulting from the difference of the paths $(\overline{ZL}+\overline{LS})-\overline{RS} = \overline{ZL}$. In practice for a base spacing of $d_B = 3$ m, the delay is $\Delta t_s = d_B/c = 3/340 \cong 8.8$ ms, while for $d_B = 4.5$ m the delay increases to 13 ms. Greater base spacing is not applied, because for $\Delta t_s > 13$ ms both reflections would be heard as separate sound impressions. The path difference for extreme positions of the source is equal to the base spacing. This difference has to be taken into account when the level difference of reflections reaching the listener is determined. Under the assumption of the spherical radiation of the source, a six decibel drop of the loudness level can be accepted for every doubling of the distance. As in a typical stereo monitoring configuration (Fig. 4) $\overline{ZL} = \overline{LS}$ and $\overline{LS} = \overline{RS}$ while $\overline{ZL}+\overline{LS} = 2\overline{RS}$, so the reflection with the possibly greatest delay is weakened by about 6 dB.

Intermediate positions of the apparent source can be localized with the application of adequately delayed and weakened loud speaker signals, reproducing delay and attenuation values, which would appear on the path from the source, through the reflection points near the loud speakers, to the listener. In order to conduct a correct stereophonic localization, binaural delays and attenuations reaching the left and right ear of the listener have to be preserved, as well as the main signal delays and attenuations of the left and right loud speaker, which in principle do not exceed 13 ms and 6 dB.

The stated top value of the main delay motivates the practice of employing in stereophony delays considerably exceeding the theoretical top limit of the binaural delays of about 0.63–1 ms, above the apparent source should invariably be in the extreme left or right position according to hitherto existing theories.

The binuaral and main delays and attenuations are separate information elements for the localization of the apparent source in an adequate point of the base width. As diagram of their time patterns, the echogram in Fig. 2 may be used, disregarding there the direct sound, marked by ① and the sound reflected twice, marked by ④.

The regard to the influence of reflections on the process of stereophonic localization leads to the neccessity of applying an intensity-phase microphone system where the spacing of microphones should be kept equal to the spacing of loud speakers in the monitoring system. This constraint and the difficulty of preserving the conformity of localization information from main and binaural delays and attenuations can make the practical application of reflective localization in stereophony difficult.

Nevertheless, the disregarding of main delays, i. e. delays between the subsequent reflections, has led in hitherto existing theories of stereophonic hearing to misunderstandings, concealments [4], or even to the questioning of generally recognized publications of experimental data [11].

8. Conclusions

The presented theory widens the konwledge of the properties of binaural hearing and explains the mechanism of subjective source localization, which up to now was presented in the psychoacoustic literature in a not quite clear and incomplete way. The theory makes possible a more effective solution of several problems of room acoustics, sound recording techniques and other applications of the psychoacoustic knowledge.

A systematic presentation of all resulting conclusions of this work has to be postponed to a separate publication. However, several more important achievments and consequences of the theory of reflective localization of sound sources are worth summing up in brief.

The mechanism of auditory distance localization of sound sources, functioning especially in rooms has been presented for the first time. If explains theoretically the localization accuracy achieved practically.

A new interpretation of the HAAS constant was given.

A common mechanism of the directional and distance localization was pointed out, as well as the contribution of early reflections in the increase of the localization accuracy.

The advantages of rectangular concert-halls were motivated by the influence of side reflections on the improvement of the discrimination of sound plans on the stage. The advantage of flat side walls in the region of first reflections was indicated.

The reason for the discrepancy of experimental data published in literature, concerning the delays between the left and right stereophonic signals was shown.

More accurate localization of apparent sources in the sound image, recorded withan intensity-phase microphone systems, was motivated.

The presented considerations of the audio-visual analogy and the postulated existence of the situation analyzer in the man central nervous organ require further theoretical and experimental research in the domain of psychophysiology. Observations made in this paper, should be the foundation for thorough investigations.

It is obvious that the presented theory can not be neither proved nor refuted with ad hoc conducted experiments. The theory of the reflective localization of sound sources can not be assessed before sufficiently numerous experimental results, will be obtained, critically checked and widely discussed.

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