

STUDIES ON DIRECTIONAL HEARING

Doctoral thesis
by

Alvar Wilska

Originally published in German as:

UNTERSUCHUNGEN ÜBER DAS RICHTUNGSHÖREN

in the special issue:

Acta Societatis Medicorum Fennicae "Duodecim"
Ser. A, Tom. XXI, Fasc. 1.
Helsinki, 1938

English translation by Matti Karjalainen
and an expert group

Aalto University School of Science and Technology,
Department of Signal Processing and Acoustics
together with the
Acoustical Society of Finland

Espoo, Finland, May 15, 2010

ISBN 978-952-60-3099-9



Alvar Wilksa serving as a subject in his own hearing experiments.

English introduction

Dear reader!

The document you are about to read has been made possible by an unusual chain of events. The basis is a doctoral thesis by Alvar Wilska, publicly defended on May 27, 1938 in Helsinki, and published in the same year (in German) in *Acta Societatis Medicorum Fennicae* “Duodecim”. This work comprises a remarkably high level of understanding of binaural psychoacoustics and of the art of creating artificial (dummy) heads. The author used these elements to perform behavioral experiments which broadened the understanding of how the hearing system extracts spatial information from the stimuli received via the two ears. It is a pity for the development of spatial hearing science that these results have gone nearly completely unnoticed. In this introduction, I will give some background on the author, address the question why he did not continue with research in this scientific area later on, and also highlight some findings of the thesis. But most importantly, it is my pleasure to introduce the English translation of the thesis which makes this work available to a wider audience.

About the author

This thesis on spatial hearing was written by Alvar Wilska, a person well known to scholars familiar with the history of technological developments, e.g., in medical research, in electron microscopy and related optical areas, but less so to scholars trained in spatial hearing. Alvar Pietari Johannes Wilska was born on March 14, 1911 in Parikkala, a community in the region of South Karelia, close to the present border between Finland and Russia. He completed higher secondary school education in Viipuri, Finland, in 1927. Then he began the study of medicine at the University of Helsinki and obtained successively the degrees of Bachelor of Medicine (1930), Licentiate of Medicine (1935), Doctor of Medicine and Surgery (1938). He was docent of Physiology at the University of Helsinki (1940), and became extraordinary professor of Physiology at University of Helsinki (1944). He was invited to the position of the Director of the Wihuri Research Institute in 1944, where he continued until the year 1947. The mission of this institute, established in 1944 by the Jenny and Antti Wihuri foundation, is to create prerequisites for high-impact research in the field of medical science.

For a short period (1959–1960), Wilska was visiting professor of cell research at the Louisiana State University School of Medicine in New Orleans. From 1960 to 1983 he was Professor of Physics at the University of Arizona in Tucson and had a close and long-lasting relation with the Philips Company as consultant on electron microscopes. In 1983, at the age of 72 years, he retired from his position in Tucson and returned to Finland. He passed away on December 22nd, 1987, in Vantaa, a city next to Helsinki.

This short introduction cannot give a balanced view of his many contributions as scientist and inventor; this will hopefully be accomplished in the context of his 100th anniversary in 2011. I have chosen to focus on his contributions to acoustics, in particular to psychoacoustics. Wilska started his scientific work at the Institute of Physiology at the University of Helsinki in the early 1930's. The institute was headed by Prof. Dr. Yrjö Reenpää (who started to publish un-

der the name Renqvist, in some articles, his name also appears as Renqvist-Reenpää). Reenpää himself was strongly interested in sensory physiology, his thesis (*Über den Geschmack*, published in 1919) focused on taste perception, and later on he published, among others, a book on sensory physiology (Y. Renqvist-Reenpää, *Allgemeine Sinnesphysiologie*, Julius Springer, Wien, 1936). Thus, the academic environment was stimulating for sensory research, but I have no indication of any prior history of psychoacoustic research. This must have emerged from Wilska's personal interest. It is known that he was involved in early stereophonic radio broadcasting experiments in Finland in the mid 1930's, so it might be that his interest in improving this upcoming technology motivated his own research on spatial hearing. In 1933, at the age of 22 years, Wilska published his first paper, together with Renqvist and Wäre, in the *Skandinavisches Archiv für Physiologie* on the influence of stimulus duration on absolute thresholds. Two years later, a paper followed in the same journal, in which he studied the amplitude of tympanic membrane vibration at the absolute threshold of hearing for different frequencies. Wilska placed iron particles on his own tympanic membrane. A magnetic field from an electromagnetic coil inside an earphone caused the iron parts to vibrate in synchrony with the magnetic field. This paper is well-recognized in audiology; in particular it is seen as the founding paper for middle ear implants. It was, e.g., already referenced in 1938 in the book by Stevens and Davis: *Hearing – Its Psychology and Physiology*. Overall, according to the ISI database, this paper has received so far more than 40 citations.

The same cannot be said for his next major publication, his thesis, published in 1938. In my nearly 30 years of research in spatial hearing, I never came across this name, and his work is also not mentioned in Blauert's book on spatial hearing. Wilska must have distributed some copies to colleagues (see below, where I describe the story of the re-discovery), because at the end of 1941, the thesis reference is mentioned in the annual literature overview of the *Akustische Zeitschrift*. This German journal on acoustics had been established in 1936, and one of the two editors was Erwin Meyer, then at the TU Berlin (he later became the 1st director of the *Drittes Physikalische Institut* at the University of Göttingen) and already a well-known name in acoustics, with his own research on spatial hearing. It is reasonable to assume that he received a copy of Wilska's work, although it remains unclear, why the work was only mentioned after a delay of several years. No corresponding reference could be found in JASA (founded in 1929), where also extensive literature overviews, including papers in German, were included in every volume.

With this publication, Wilska's contribution to the acoustic literature ends because he focused his interest on microelectrodes, his next invention. Using this method Ragnar Granit received the Nobel Prize in 1967. The nine papers he published in 1939 mostly focus on measurements of action potentials in single nerve fibers of both muscles and the retina. In 1942 he published his first paper that addressed the possibility of stereoscopic X-ray analysis, used for removing foreign objects from wounded soldiers, thereby indicating his future focus on imaging technologies for medical applications. His wife, Dr. Maija Wilska, explained to me these recurrent shifts of interests in the following way:

“I think the reason is that he was always full of new ideas about improving equipment and methods, which he felt was his duty. Therefore he did not take the time to work extensively with these new methods.”

Of course, also the beginning of WW II, in which Finland was involved since the end of 1939, influenced Wilska's work, since he became strongly engaged both as a medical and technical specialist. Among other topics, he was involved in technologies for sound-based localization and bearing estimation of artillery projectiles, but this work was, as far as I know and most understandably, never published.

The thesis

The work in the thesis revolves around two experimental questions:

1. What is the influence of external factors, e.g., stimulus parameters, on spatial hearing?
2. How do signal parameters influence localization accuracy?

These experimental questions are well-embedded in and motivated by a discussion of the state-of-the-art in the first section, entitled *Historical critical issues*, by comparing and criticizing experimental methods used by other experimentalists and by borrowing, where possible, also from techniques used in other sensory modalities and physiological insights. This section is an excellent introduction to the knowledge available at that time, and it clearly reflects the then ongoing controversies in theories of spatial hearing. Particularly appealing to me is Wilska's countering of arguments which had been brought forward against the time theory of spatial hearing. The arguments (see p. 2) refer to the extremely low values of possible interaural time differences, which are orders of magnitude smaller than the temporal limit of separating two successive monaural sounds. He emphasizes that these two percepts cannot be compared in such a way:

“In sound localization it is not a question of separated perception but rather whether the direction perception has attributes of wholeness.”

The next, and in my view highly innovative aspect, is contained in the section: *Methodological – Technical issues* (p. 7). Here he describes, among others, how he built his own dummy head. In contrast to other attempts from this period (Firestone, JASA 1930; de Boer, Philips Tech. Journal 1939), he did not base the head on a shop-window dummy, but being a physician, on the head of a male corpse. By molding positive and negative versions of the head he not only replicated the outer form of the head, but also ensured a correct representation of the ear canal up to the presumed position of the tympanic membrane and the detailed structure of the pinnae. To my knowledge, this replication of the outer ear had not been included before with such detail (and Wilska had good reasons why he wanted to replicate also this part). In de Boer's work, the outer ear is not at all modeled and the ear canal is much wider than in humans. *Oscar*, the dummy head developed at Bell Labs (June 1933), also does not seem to have so minute outer ear features and the ear canal opening again appears to be wide. Another detail mentioned by Wilska concerns the size of the microphones. In order to match the size of the ear canal, he built his own condenser microphones with a diaphragm diameter of 13 mm and placed them in the dummy in such a way that they formed an angle with the ear canal in correspondence with human anatomy.

A first set of experiments in his thesis was to measure the absolute threshold of hearing for various source directions, covering three orthogonal planes (most previous research had focused

only on the horizontal plane). By occluding one ear, the change of absolute threshold with the source direction was a direct reflection of the (amplitude) component of the ear's directional transfer function. Since such a threshold method does not give any insight into the interaural time difference, he used his dummy head for this purpose. He replaced the human observer with the dummy, connected the two microphones to two oscilloscopes in close proximity to each other so that the phosphorescent displays could be captured on a single camera's film (see Fig. 9). In this way, he could establish the direction-dependent values of the interaural time difference and the interaural intensity difference for different frequencies (see Fig. 10). He compared his experimental data with the prediction for ITDs using the relation proposed by [VON HORNBOSTEL and WERTHEIMER \(1920\)](#). It appeared that his differences were somewhat larger (head width parameter 24 cm instead of 21 cm) than those typically used, and this led Wilska to the statement (p. 18):

“It must be mentioned, however, that the cadaver head used as a model of the artificial head was exceptionally large.”

Wilska was very well aware of the consequence of such transfer characteristics for broadband stimuli. In Fig. 11, he shows how the waveform of a harmonic complex tone varies with the source direction, due to the introduction of phase changes and frequency-dependent attenuation. The spectral filtering introduced by the head and the outer ear played for him a strong role in spatial hearing, and that led him to favor sounds with a continuous, broadband spectrum as being most easy to localize.

“Our directional hearing of noise signals, based on the difference in sound color, deviates from directional hearing of complex tonal signals mainly because in the former case during the assessment of source direction the smallest nuances in sound color are also perceived, because the noise spectrum, as mentioned, is continuous. We can also see that in this respect noise must be the easiest of all sounds to localize. Due to this the intensity theory loses its meaning, being limited to pure tones that almost never occur in nature, and I suggest it be renamed *sound color theory*” (p. 23).

And he closes this section with the statement (again on p. 23):

“Following these theoretical argumentations we have to assume that noises are a prominent element of our directional hearing.”

The following parts of the thesis deal with the resolution of spatial hearing, or, in modern terms, the *localization blur*. For these measurements, he positioned two loudspeakers with a specific, adjustable difference in direction at a distance of either 6 or 2 m and fed noise bursts successively first to one and then to the other speaker. The subject had to indicate if he heard the second sound burst to the right or left of the first burst. The smallest angle difference, at which this was possible without judgment error, was used as the discrimination threshold. Measurements of this localization blur were performed again in the three different planes (not by re-orienting the sources, as we do it nowadays, but by re-orienting the subject's central axis, see description on p. 11), and gave for the horizontal and the frontal plane the well-known result

of a high resolution for frontal incidence and a much larger blur for sources placed to the side. The data could be fitted nicely by assuming that at the discrimination threshold, there is a constant change in interaural time differences between the two loudspeaker directions. Regarding localization blur values in the *median* plane, Wilska was less successful:

“It was also attempted to use this method to determine the directional hearing thresholds in the median plane. I noticed soon, however, as expected, that the threshold angles were very large ($> 30^\circ$) and indeterminate, so that the method was found unsuitable for the purpose” (p. 28).

These measurements of spatial resolution were repeated for a number of parameter variations, including the bandwidth of the noise, the influence of occlusion of one ear, the duration of the onset and offset ramps, and the influence of signal type (noise, pure tones, and complex tones). From the literature Wilska knew that localization of pure tones is strongly dependent on the onsets and offsets, and that it is much harder to localize continuous tones. He measured the localization blur as a function of the ramp duration for pure tones and concluded that:

“... if the onset and offset times increase approximately logarithmically, the directional hearing thresholds grow nearly linearly” (Table 5, p. 33).

The really big step forward is contained in his insight regarding the onset and its role as a temporal marker, and that broadband signals, like complex tone mixtures and noise bands contain such temporal markers also in their ongoing *envelope*. That is, why the spatial resolution for tone mixtures is high and is not influenced by the onset ramp duration:

“This is easy to understand, however, if one knows that such a superposition of two tones of different frequencies produces continuous amplitude variations, and the fade-in and fade-out occur so often per second as indicated by the frequency of the difference in tone” (p. 34).

I wish to conclude this overview by referring to his overall discussion of experiments on spatial impression, on the localization accuracy, as well as on the importance of time and intensity differences on binaural-electrical transmission of sound (p. 37). He discusses perceptual differences between listening monaurally and binaurally, the influence of the distance between the recording microphones, front-back confusion, the influence of lack of visual impressions, and the accuracy with which sounds recorded via the artificial head and reproduced via headphones could be localized.

“It is remarkable that from these artificial head experiments one can obtain only the azimuth angle of sound, while the precise projection, i.e., the choice between front, rear, top, bottom, etc., is completely absent. One might think that our experience on such localizations was limited to our own head, and that the artificial head reproduces these delicate sound color manifestations to us in a ‘foreign language’. We would underestimate the sound reproduction capabilities of the artificial head if we did not discover later that even when listening with open ears, the time-difference-equivalent directions are often confused” (p. 41).

Even though in this introduction I have only touched on a small part of Wilska's observations and reflections, I hope that I have stimulated the reader's curiosity to enjoy the entire text. After all, this had happened to me when I first had read the original text in German, sometime back in 2007, and was really overwhelmed by the ingenuity of this work. It is hard to believe that this research was carried out some 75 years ago.

The re-discovery of Wilska's thesis

You might wonder how, after this long period, we managed to re-discover Wilska's thesis. For me, it started with the thesis of Nico Franssen which I acquired from my favorite local second-hand book store a few years ago. Franssen is known to the binaural world due to the localization effect named after him, and for me, he is also known as a former leader of the acoustic research group at the Philips Research Laboratories in Eindhoven. The thesis with the title *Some considerations on the mechanism of directional hearing* describes work performed at the Philips Research Laboratories, and it was defended at the Technische Hogeschool (Polytechnic) Delft on July 6, 1960. This thesis contained references to a great number of studies and authors which were familiar to me from my own work. However, at four different and quite prominent places, reference is made to "A. Wilska, *Untersuchungen über das Richtungshören*, Akad. Abhandl., Helsinki 1938". Given the range of page numbers referred to by Franssen, it must have been a somewhat longer text, but there was no traceable journal, or school mentioned, so I did not pursue this any further.

Then in 2006, I was invited by Matti Karjalainen to be the official opponent for the Ph.D. defense of Juha Merimaa (*Analysis, synthesis, and perception of spatial sound - binaural localization modeling and multichannel reproduction*), at TKK (now Aalto University School of Science and Technology) in Espoo, Finland, on August 11, 2006. After the successful defense, I approached Juha to ask whether he could try to get a copy of Wilska's text, based on my scarce information. Juha not only managed to get a copy, but sent me the whole text as a PDF file. At that time, it had become clear that the text represented Wilska's Ph.D. thesis.

The next episode was a short talk that I gave in a session on the History of Acoustics at the joint Dutch-German Acoustic (NAG-DAGA) conference in Rotterdam, March 2009, with the title: *Early research on binaural hearing in Helsinki and Eindhoven*, which addressed both the thesis by Wilska and the one by Kornelis de Boer (a well-known acoustician from Philips Research): *Stereofonische geluidswaergave, (Stereophonic sound reproduction)*, TH Delft, December 6, 1940. This talk was well-received, so I continued by planning a longer presentation, focusing just on Wilska, in my monthly sound perception seminar at the Eindhoven University of Technology at the end of April. The announcement of this seminar was also received by one of my close colleagues at Philips Research, Aki Härmä, who, having been a member for many years of the former Acoustic Laboratory at TKK Espoo led by Matti Karjalainen, forwarded the abstract of my presentation to his former colleagues in Finland. And this initiated a cascade of events. The next morning, Toomas Allosaar from the same laboratory responded that he used to be a neighbor of the Wilska family and that he had, until recently, been in email contact with Dr. Maija Wilska. Later that day, he had renewed that contact and wrote: "I just spoke with Dr. Maija Wilska and she would be happy to help you with any questions related to her husband's work." With still a week to go until my presentation, Maija offered me a substantial amount of background information and sent me a number of documents, like newspaper reports on Wilska

from the New York Times and the Arizona Daily Wildcat, plus a number of photos and a CV. All this arrived in my mailbox on the morning of my seminar presentation. And, as a proof of how small the world is, I would like to add the following sentences from one of her correspondences:

“You may not know that Alvar had close connections with Philips Eindhoven being their consultant in electron-microscopy. Dr. Bill van Dorsten was a close friend and many persons from Philips visited frequently in Tucson, possibly partly because they liked to visit a country completely opposite to Holland - sun and mountains. We visited Eindhoven with children too and have pleasant memories.”

In the following weeks, Matti took up contact with the Finnish Broadcasting Corporation (YLE), to determine whether there was any material left from Wilska's time. One of our wildest dreams was that we hoped to find the artificial head he had built. But nothing could be found. However, Aki Härmä discovered that in the department of history and philosophy of the University of Tampere, Sampsa Kaataja had written a Ph.D. thesis on Finnish university researchers' contributions to technological innovation in which a chapter was devoted to Alvar Wilska.

Soon the idea evolved to translate the whole thesis into English. Several approaches were discussed between Matti, Aki and myself, including trying to obtain a grant, maybe from one of the Academies, the European Acoustics Association, or the Acoustical Society of Finland, but the largest problem for us was to find a person with a good knowledge of (spatial) hearing (also in the historical perspective), German, and English, and who was able or willing to invest considerable time and effort into this endeavor. And then, while no simple solution appeared, Matti himself started to translate the first parts. At one point he announced that he had already translated 32 pages, and not too long afterwards, a first draft of the English version was available. This version was shared between a number of binaural experts, and all this has finally led to the version that you find on the following pages. For those who are interested in the original German text, we have included a scanned version of the thesis from 1938 at the end of this document.

Working on this project was certainly great fun for all involved, since at any given moment a new surprising bit of information would turn up. I personally want to thank Matti Karjalainen for his energy and driving force that was essential in realizing this endeavor in such a short period of time.

Armin Kohlrausch

Eindhoven, The Netherlands, May 2010



Wilska's main interest in later years were microscopes.

About the English translation

When the doctoral thesis of Alvar Wilska was 'rediscovered', thanks to Dr. Armin Kohlrausch, it became obvious that, in order to make it known to the present day acousticians and spatial hearing researchers, it should be translated to English. We considered different ways of organizing the task and found it challenging. In addition of mastering both English and somewhat old style German with complex sentence structures, the translation required good knowledge in acoustics in general, in physiology and psychology of hearing, as well as electronics and analog signal processing. Not an easy task for any individual.

Finally, I decided to volunteer and began work on a raw translation, leaving other experts to polish the result. In spite of my rusty German and non-native English, but having a fairly good background in spatial hearing and electronics, I managed to produce useful groundwork. After some preliminary feedback from several interested readers, Dr. Toomas Altonsaar touched up the English for improved readability. I then asked a few experts in hearing-related topics, each being bilingual in German and English, who were native speakers of German, to read the translation carefully, especially where difficult concepts and expressions existed. These experts were Prof. Jens Blauert, Prof. Armin Kohlrausch, Dr. Stephan Paul, and Dr. Carl Poldy (in alphabetical order). I am very grateful to them for their efforts and spending time to improve the translation. Finally, I integrated their recommendations and produced this version for publication. I accept full responsibility for the final decisions and possible mistakes concerning concepts, terms, and expressions used in this translation.

In order to make the translation most readily available to the research community, it was decided to publish it as a freely available PDF document on the Internet. Also, it was decided to republish the original German version so that curious minds could check the exact wording of the author if they are skillful enough in German. Finally, since some researchers still rely on documents printed on paper, the combined English-German version has been made available as a report that can be ordered from the Aalto University School of Science and Technology, Department of Signal Processing and Acoustics. Some "academic advertising" is needed to make these sources known to researchers. We hope this arrangement makes sense and will be of benefit to the potential readers.

On behalf of the translation team,

Matti Karjalainen

Espoo, Finland, May 2010

Two weeks after completing this translation, Matti Karjalainen passed away on May 30th, 2010.

Foreword (by Alvar Wilska)

This work has been accomplished for the main part in the Institute of Physiology at the University of Helsinki. It is my sincere desire to express my deepest thanks to the director of the Institute, Prof. Dr. Y. REENPÄÄ, who has followed my work with tireless interest, and who has encouraged it by well-meaning support of all kinds. Thanks to him, the newest scientific facilities have been made available for my work; his generous response to all my plans has greatly facilitated my task.

It is my duty to thank the *C o n s i s t o r y* of the *U n i v e r s i t y* of *H e l s i n k i* for their financial support that has made possible the purchase of some of the important equipment necessary to carry out my work.

I would also like at this point to cordially thank the managing director of the Finnish Broadcasting Company, M.Sc. J. V. VAKIO, for his permission to use the technical facilities of the company in my preliminary studies. I also thank all my helpers, test subjects and all other persons who have contributed to my work in any way.

Table of Contents

<i>Historical – Critical Issues</i>	p. 1
<i>Methodological - Technical Issues</i>	p. 7
<i>Studies on the external factors effective in directional hearing</i>	p. 10
Investigations on intensity relations by hearing threshold experiments	p. 10
Artificial head experiments for the investigation of intensity and time differences in directional hearing	p. 15
The importance of noise on directional hearing in the light of these results	p. 20
<i>Studies on the directional resolution of hearing</i>	p. 24
General aspects	p. 24
Determination of directional hearing threshold using impulse noise	p. 26
Experiments with unilateral ear closure	p. 30
On the impact of "pulse sharpness"	p. 32
On the impact of onset and offset time	p. 32
Directional hearing experiments with tone complexes	p. 34
Directional hearing experiments with continuous noise	p. 35
Directional hearing experiments with continuous tones	p. 35
Experiments on the significance of phase differences in directional hearing	p. 35
Experiments on spatial impression, on the localization accuracy, as well as on the importance of time and intensity differences on binaural-electrical transmission of sound	p. 37
Experimental studies on the properties of our listening space	p. 41
<i>Considerations on the propagation of directional hearing stimuli in the auditory pathways</i>	p. 46
<i>Final remarks</i>	p. 48
<i>Summary</i>	p. 51
<i>Literature references</i>	p. 53
<i>Appendix: Additional photos of the artificial head</i>	p. 55

Historical – Critical Issues

Most authors agree that, in order to perceive sound direction, some differences must exist between the excitations of the two ears. However, the nature of these differences, resulting in directional hearing, is still (1938) a controversial question. Directional hearing has been explained mainly on the basis of three theories, namely, the intensity theory, the phase theory, and the temporal theory.

Intensity theory: The ear that is directed toward the sound source (the ipsilateral ear) is more exposed to sound radiation than the other one (the contralateral ear). The difference in excitation strength between the ears results in the perception of direction.

Phase theory: Due to the distance difference, the ipsilateral ear receives the sound wave with a different phase than the contralateral ear; this phase difference is the prerequisite for direction perception.

Temporal theory: The ipsilateral ear receives the sound earlier than the contralateral one; the time difference causes the perception of direction.

Let us first look at the *intensity theory* in somewhat more detail, assuming that the sound source is in the median plane. Then the radiated sound appears equally strong at both ears and we localize the source accordingly in the middle. The more the excitation by the sound source moves to the side, the larger becomes the intensity difference between the right and the left ear, which results in side localization. This intensity difference is caused not only by the different distances of the ears to the source but also because the ipsilateral ear is in a better position to capture the sound source than the contralateral ear. It is known that all obstacles in the sound path create a "sound shadow" that is more prominent the higher the frequency of the tone is. According to studies by TRÖGER (1930), the head starts to shadow sound increasingly from 300 Hz up, and already at 2000 Hz the level in the direction perpendicular to the external ear is much higher than in other directions.

Although the intensity theory cannot be considered as the basis of directional hearing, as we will see later, it has had several proponents [GATSCHER (1924), KREIDL and GATSCHER (1920, 1923), BRUNZLOW (1925)].

As opponents to the phase theory, KREIDL and GATSCHER (1920) argue that only the sound intensity between the ears can be utilized in the localization of noise, because phase differences cannot be found with noise. Against the temporal theory the mentioned authors (1923) raise the objection that two sound signals, arriving at the ears one after the other, can be separated only when the interval corresponds to 0.03 seconds for noise and 0.0175 seconds for tones. Based on this observation, the temporal theory, involving far smaller time differences, is to be rejected as untenable.

In my view, the latter test results do not show any evidence against the temporal theory. In sound localization it is not a question of separated perception but rather whether the direction perception has attributes of wholeness. If the interaural time difference is made artificially longer until we can hear the sounds in this sense "separated", the conditions for directional hearing become quite unnatural.

BRUNZLOW (1925) made his preliminary tests using tuning forks and telescopic tubes. Test subjects with different hearing ability on the right and left side found the subjective auditory

image moved to the side of the better-hearing ear in the case of equal path lengths. If the shank of the tube on one side was lengthened until the sound image was exactly in the middle, one could thus obtain a measure for the mutual relationship in hearing ability of the two ears. BRUNZLOW's explanation of this phenomenon is that the shank extension implies attenuation of the sound intensity at that ear, and thinks this proves that the phenomenon of the moving of the subjective auditory field is elicited by a change in intensity. On the basis of his findings he did not consider binaural arrival time differences in his further studies.

Further determination of the direction discrimination threshold in the horizontal plane led BRUNZLOW to experiment with a [fallphonometer](#). A particularly low directional threshold was found in two cases: just in front and sideways in the back. These are the points at which, in the back, all sounds from the rear are shielded by the pinnae and at which, in the front, all sounds from the contralateral side are shielded by the forehead. Here something happened, analogous to his ear trumpet experiments made earlier, when the sound source was moved outside of the funnel opening angle. According to BRUNZLOW, monotic sound localization is an element of our spatial sound perception and consists of the ability to recognize the changing position of a sound source with respect to the ear. The recognition of the change in position is made possible by changes in the quality of the sound impression that we perceive and improves as a function of our timbre analysis ability. This change in the sound quality depends in the end on the changing damping of a sound mass, depending on whether the ear is facing towards or away from the sound source.

According to BRUNZLOW, the "central" hearing areas of the right and left ear are separated, but overlap each other, like the visual fields in animals whose eyes are on the side of the head. In his view there is only one binaural hearing range that indeed reflects the character of the "peripheral" one (attenuated one), which is the rear range. The sound impressions coming from somewhere on the side are central only to one (ipsilateral) ear, while to the other (contralateral) they are peripheral; for these sounds the perceived intensity and quality vary considerably, and their mutual relationship will vary depending on whether the sound is coming purely from the side, directly from front or from a direction between them. This qualitative change is perhaps the decisive factor in binaural sound perception that strongly speaks against time and phase differences. That these differences also affect the sound image is, however, not disputed by the author.

The preliminary experiments made with telescopic tubes, on the basis of which BRUNZLOW believes we are allowed to completely discard binaural time differences, are in my opinion not conclusive enough. It must be remembered that the propagation of sound in such tubes as a result of reflections and the resonance of air columns is different from that in open air. Furthermore, the lengthening of one tube also results in differences of phase and time.

It is known from studies by [KLEMM \(1920\)](#), [BÉKÉSY \(1930\)](#) as well as [SHAXBY AND GAGE \(1936\)](#) that, when the subjective auditory image is on the side of the stronger sound as a result of an intensity difference, this effect can be offset by an opposite time difference so that the auditory field is again brought to the center. According to [HALVERSON \(1922\)](#), a deviation of the sound image of 8° can be obtained by an intensity difference for trained subjects, for others maximally 40° , but never for 90° , and according to his experiments an authentic sound image migration can never be achieved by intensity differences. In the experiments of [STEWART \(1920\)](#) the intensity ratio was varied in both ears and the phase difference was kept constant. If the phase difference was 0, then the sound

image shifted from the median plane to the side of the more strongly excited ear. However, this shift did not correspond to the calculated values but amounted, for example, at 60° only to $9\text{-}14^\circ$ (for tones of 512 and 1024 Hz). In addition to this moving sound image, also a static one was perceived in a direction corresponding to the phase difference (for phase difference 0 in the median plane). By changing the phase difference and keeping the same intensity, the observed directions coincided well with the calculated values, but from 1200-1500 Hz upwards the effect of the phase difference disappeared, and the sound image remained in the median plane.

According to studies by [HECHT \(1922\)](#), [TRIMBLE \(1929\)](#), as well as by [STEVENS and NEWMAN \(1934\)](#), the intensity differences are decisive for localization at high tones and the phase differences at low tones.

While the localization ability for lower tones is not explained satisfactorily by the intensity differences, it is considerably easier to explain it by the *p h a s e t h e o r y*. When a tone (sine wave) reaches one ear earlier than the other one, also the phase in the first ear is earlier than in the other one, and according to the theory this phase difference would cause our direction perception. The phase difference is $P = 0$ if the sound source is in the median plane of the head; it grows with displacement of the sound source to the side, and reaches its maximum when the sound source lies on the ear axis. Since the sound needs to travel around the head, instead of the straight distance between the ears, we must accept the empirically determined constant $k = 21$ cm by [VON HORNOSTEL and WERTHEIMER \(1920\)](#) as the basis for the calculations of phase differences.

The phase difference P increases with frequency, in other words with decreasing wavelength λ , until it becomes $\lambda/4 = k = 21$ cm when the sound source is on the ear axis. The frequency corresponding to this wavelength is 400 Hz. At higher frequencies P becomes ever smaller, and at the frequency of 800 Hz, where $\lambda/2 = k$, the wave phases "neutralize" each other. With further increase in frequency the phase difference increases and reaches its second maximum at $3\lambda/4 = k$ (frequency 1200 Hz), after which it is reduced until it becomes zero again at $\lambda = k$ (frequency 1600 Hz).

If we expose the ears to two very slightly detuned tones, each one sent exclusively to one ear, a continuous change of the phase difference for constant intensity of the stimuli is obtained, and one will hear a single tone running around in a circle ("rotating tone")¹. Since these rotational tones seemed to describe a closed orbit, the apparent direction angles φ were assigned to the phase differences P [[FRY \(1922\)](#)] as shown in Fig. 1 ($0^\circ =$ median plane, $90^\circ =$ ear axis).

Now, if the perceived direction is dependent on the phase difference as shown in Figure 1, then, with a continuous change of frequency of a stationary sound source, the subjective sound image would rotate around on a circle. The investigations of [BOWLKER \(1908\)](#), [STEWART \(1920 I\)](#), [HALVERSON \(1922\)](#), [VON HORNOSTEL \(1923\)](#) have however shown that this is not the case, but rather does not return the subjective sound image back to the median plane for phase differences between $\lambda/4$ and $\lambda/2$, and to achieve a deviation of 90° , a larger phase difference is needed the higher the frequency is. The sound image then remains at 90° up to a phase difference corresponding to $\lambda/2$, at which point it disappears. At the same time, a sound image appears on the opposite side at 90° and migrates to the median plane, which it reaches at $P = \lambda$. This is illustrated in Figure 2, the curve is valid for 500 Hz. The two curve branches found between 0 and λ approach each other with increasing frequency until they overlap at

¹First described by S. P. THOMPSON in 1878; ref. in [VON HORNOSTEL \(1922\)](#).

frequencies above 800 Hz, as shown in Figure 3 (at frequency 1000 Hz). If the frequency is further increased to 1600 Hz, then the two curves extend over the whole area from 0 to λ . For frequencies between 800 and 1600 Hz one should be able to perceive simultaneously two sound images, which are at 800 Hz on the opposite sides of the ears' axis, but with increasing frequency form an ever smaller angle until they coincide at 1600 Hz in the median plane.

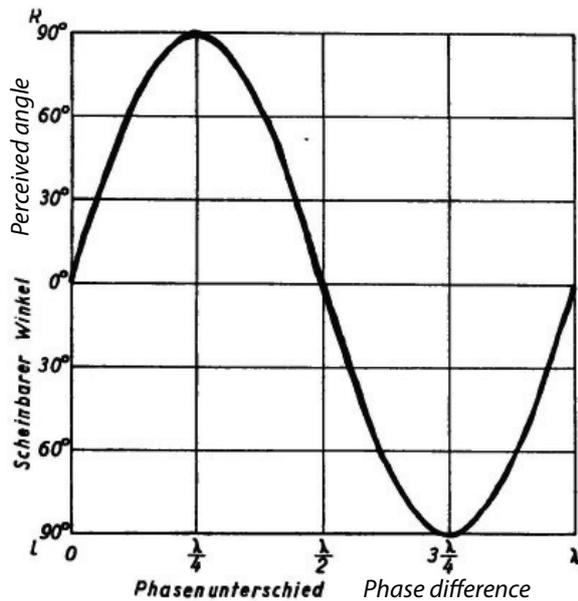


Figure 1: Dependence of the 'apparent' phase angle difference on the direction according to the older view.

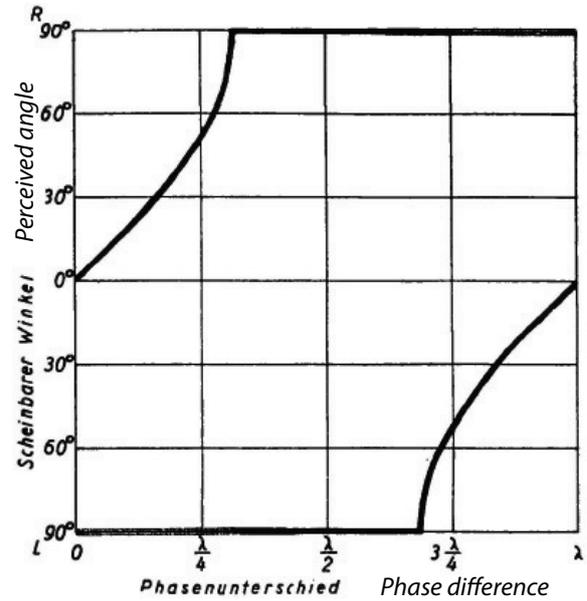


Figure 2: Dependence of the 'apparent' phase angle difference on the direction according to the new view; Frequency 500 Hz.

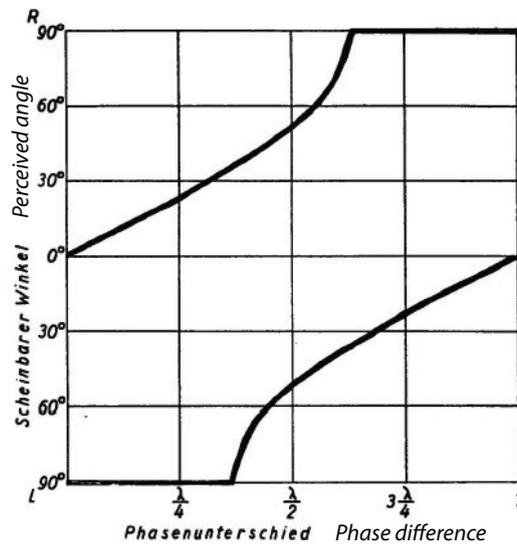


Figure 3: As in Fig. 2, but frequency is 1000 Hz.

According to [VON HORNBOSTEL \(1926\)](#) the following relations are given between the apparent direction and phase difference:

1. The direction is on the side of the leading phase.
2. The angle to the median plane (φ) grows with increasing phase difference (P), and indeed in the same way at all frequencies: the curve representing this relationship is a sine curve ($P = k \sin \varphi$).
3. The angle associated with a particular phase difference increases in proportion to the frequency. For example, the curve depicted for 1000 Hz (Fig. 3) will become the curve for 500 Hz (Fig. 2) if we double the x-axis scaling, i.e., putting $\lambda/4$ in the place of $\lambda/2$, etc., and moving the lower branch of the curve parallel to itself to the right by the (old) length λ . But that means nothing other than this, that not only the form but also the absolute size of the two branches remain the same at all frequencies when we introduce a scaling of the abscissas not as fractions of wavelengths but as an absolute measure (cm). If we do that, then the following results:
4. To the angle of 90° corresponds the abscissa of 21 cm (in the upper branch of the curve; in the lower $\lambda - 21$ cm).

The meaning of the phase theory is, of course, limited to pure tones. In daily life, pure tones are a rarity; as objects of our auditory world, noises are much more common than tonal sounds. In directional hearing of noise, in addition to differences in intensity, only the *temporal shift* of the excitations on the ears needs to be considered. According to [VON HORNBOSTEL and WERTHEIMER \(1920\)](#), the above declared rules for tones remain valid also for noise when the time difference Δt is used instead of the phase difference P . According to them, the *temporal theory*² is thus substituted in place of the phase theory. The perceived angle follows the relationship: $\sin \varphi = \Delta s/k = 34000 \cdot \Delta t/k$; (Δs = the path length difference in cm, $k = 21$ cm, Δt = time difference in seconds; 34000 = the speed of sound in cm at room temperature).

According to the investigations of [KLEMM \(1920\)](#), the binaural time threshold is smaller than normally encountered (= not with separate ears). He has conducted his experiments with a [Helmholtz pendulum](#) for the production of electrical current pulses and two telephones to listen to them. The usual time threshold (where two acoustic stimuli are still heard separated) is about 2σ . In binaural reproduction, subjective perception from two sound directions will still be valid when the time difference between the two sound stimuli is no longer perceptible. If the time difference is reduced to $1.8\sigma - 0.13\sigma$, then most subjects will merge both sources into a single sound percept, and the localization of this sound perception occurs on the side of the sound heard first until a time difference of 0.61σ is reached and sometimes even down to 0.002σ .

According to the investigations of [ENGELMANN \(1928\)](#) on sound localization in animals we have to assume that the value of k varies with ear distance. These very carefully arranged trials with pets (dog, cat, chicken) show that the animals, despite their small ear distance (dog 9-13, cat 6.5-7, hen 3, chicken 1.5 cm), can distinguish much smaller directional differences than humans. It is also noteworthy that a dog does not perceive the acoustic distances, while a cat has a very fine skill to discriminate them.

One could imagine that it would be necessary to have a sophisticated brain for directional hearing. Specific experiences from the behavior of insects show, however, that also they have the

²First MALLOCK 1907, then VON KRIES 1913. Ref. [VON HORNBOSTEL \(1922\)](#).

ability of orientation in space based on sound, despite their primitive nervous system. [REGEN \(1924\)](#) has found that the female cricket, when it is in sexual drive, is directed at least from 10 m to move towards the chirping male. Once the male stops chirping, the movement of the female becomes disoriented. After destruction of the tympanic organ, the female no longer finds its target. In unilaterally operated females the movement is not directed anymore, and the motion requires a much longer time than usual. That really this stridulation sound, not the scent, attracts the sexes together is fully demonstrated by [REGEN](#). While male crickets were chirping in front of a microphone, he brought the telephone into another room where the female was. When the microphone was switched on, the female then immediately moved towards the sound reproduced by the telephone; if the connection was interrupted, the female wandered away from the telephone.

Since the beginning of air warfare, much work has been devoted to the study of directional hearing. Detecting enemy aircraft at night, during dense clouds and fog, is a prerequisite for successful defense. Under such circumstances, the eye is useless. With ears only, exact determination of sound direction is more difficult than with *stethoscopes* designed for this purpose. In relation to the type of direction finding these fall into two groups. One group is based on the maximum principle, i.e., the acoustic axis is sought in the direction of maximum aircraft noise. The other group, to which most of the listening devices belong, is based on the binaural principle. The main difference compared to normal hearing is the artificial extension of the ear base (k) by tubes and funnels, which also amplify the sound. If one brings the receiver funnel to distance b , the perceived direction angle φ is increased compared to the true angle α , and in this way one can still distinguish directions which merge together to the naked ear. The true angle is derived from the perceived one by the relation ($\Delta s =$) $b \sin \alpha = k \sin \varphi$ [[HORNBOSTEL \(1926\)](#)]. Most listening devices have two bases, one for the determination of the azimuth and one for the elevation angle.

According to studies by [AGGAZZOTTI \(1921\)](#), [LACHMUND \(1921\)](#) and [PEREKALIN \(1930\)](#) the localization of prolonged sounds is much more difficult than that of periodically interrupted tones. The beginning and the end of a sound stimulus seem to be crucial for localization.

Regarding the influence of vestibular stimulation, [RAUCH \(1922\)](#) indicates that in vertigo either a complete disorientation occurs or that the sound is localized in the sense of rotation direction, but rarely in the opposite or even in the correct direction.

Similar results were obtained by [ALLERS and BÉNESI \(1922\)](#). [GOLDSTEIN and ROSENTHAL-VEIT \(1926\)](#) have found that a sound localized in the median plane, when the observer turns his eyes sideways, will be moved to the opposite side. If on the other hand he keeps his eyes fixed to the center direction and turns his head, then the sound image moves in the same direction to which the head is turned. The function of the labyrinth plays, as [TULLIO \(1926\)](#) among others highlights, a major role in directional hearing and generally in the recognition of a three-dimensional space.

The studies referenced in this chapter form the basis for the physiology of directional hearing. Later, in the context of my experiments, I will present in more detail the results of many authors not mentioned here since those results will be easier to understand by the reader on the basis of prior technical etc. knowledge that has been clarified here.

Methodological - Technical Issues

While I have used so many technical tools in my study that their description together with the experimentation itself would be a problem, it is perhaps suitable here to introduce briefly some of the most utilized devices. On the basis of this preliminary description of the most important equipment at my disposal, the combinations of equipment used in later experiments will be made easier to understand by the reader.

From the first experiments³, of which most were conducted in the building of the Finnish Broadcasting Company, the necessity of an acoustic experimentation room became increasingly evident. In the basement of the Institute of Physiology there was a room suitable for this task, with dimensions of 7 x 3.5 x 3 meters. To keep this room as anechoic as possible, the walls and other surfaces were covered with corrugated cardboard. It was folded in such a way as to form large vertical grooves of 0.5 meters in width and 0.3 meters in depth, thus forming a vertical cavity between the cardboard and wall, which was then filled with cotton wool. Then the walls and ceiling were covered by folded, thick woollen cloth, and the floor was covered with a double thick carpet.

Near to this room, which I call the *recording room*, were two other available rooms; one could be called the *generator room* and the other one the *analysis room*. In the former one there were two AC (alternating current) signal generators, one constructed in the way of GILDEMEISTER and KOCH and the other one similarly with a push-pull oscillator circuit but with capacitive coupling. Both were capable of producing practically pure sine wave AC currents from 30 Hz up. For further purifying of the sine waves from overtones I constructed a seven-octave filter that was composed of three-stage filter sections. It was necessary to use these octave filters only in exceptional cases, because the sine wave purity of the AC currents was good, as already mentioned.

Loudspeakers and headphones were used to convert the AC currents from the generators to corresponding sound signals. In some experiments harmonic overtones were used, achieved by changing the coupling, by series capacitors in the loudspeaker circuit, etc. Beating, tone mixing, etc., were produced in a typical way by simultaneous use of both generators. A more detailed description of the methodology will be given in the context of the experiments.

The amplifiers were situated in the analysis room, along with two cathode-ray oscilloscopes with their supply voltage and sawtooth sweep oscillator, an Edelmann type of camera with electric drive unit, a movie camera, etc. Between the electrical connectors in the recording room and the contacts with corresponding numbering on a table in the analysis room, six low-capacitance grounded cables were installed. Thus it was possible to make all necessary connections between the recording and analysis rooms.

I selected the transducers used as *sound sources* from a large number of Celestion-Permanent-Dynamic loudspeakers (type E. 5.) so that two such units had at all frequencies a similar sound response. To provide a sound radiation that was as much as possible "pointwise", each loudspeaker was attached to the inner side of an iron plate with a circular opening of 3 cm in radius. This plate was assembled to the end of a 30 cm long iron tube of 13 cm in diameter and 0.5 cm of wall thickness. The free volume inside the tube was filled with shredded paper and the other end was closed with a seal plate made of iron. Each loudspeaker was placed on a wooden block, and on the side of this block was the connector.

It was verified that sound from the system was radiated only from the opening at the end of the

³Here the original copy had some missing words.

iron tube and not from other points. If the opening was covered for example by the palm of the hand, the sound radiation was reduced to a minimum, which was mainly radiation through the hand to the surrounding air.

For recordings, *condenser microphones* of my own construction were used. Their membrane was 0.04 mm thick and 13 mm in diameter. The membrane was tightly spanned so that its eigenmodes were above the hearing range. The carefully isolated backplate was adjusted to a distance of about 0.01 mm from the membrane. In spite of their small dimensions the microphones had good enough sensitivity.

The circuit diagram of the *microphone preamplifier* was a resistance-capacitance connection. The metal casing of the preamplifier was tower-like, and in its upper part there was a hole that included a screw thread for fastening the microphone. The heater and anode batteries were in the same room as the preamplifiers and they were connected together with flexible cables. From each amplifier, a low-capacitance cable was fed to the switchboard of the recording room.

A difficult task was the construction of the *artificial head* used for oscillographical and acoustical analysis. For this purpose I received from the university's Institute of Anatomy a male cadaver head that was used as a model. After the head was smeared with vaseline, gypsum powder and water were mixed and this pulp was poured into a cardboard box. The head was sunk into the mix so that its left side sunk up to its middle line. After the gypsum had hardened the head was removed and the negative impression of the left head side was ready. In a likewise manner, the negative impression of the right side of the head was produced. When the negatives were dry, they were smeared with vaseline and the construction of the positive "scull shell" commenced. For that, pieces of gauze with dimensions of about 30 x 30 cm were sunk into the gypsum mix and overlaid layer by layer on the inner surface of the negative until the thickness of the gypsum-gauze layer was about 1 cm. When hardened, the constructed positive was taken apart. After the removal of extra rims, a very good replica of the original head halves was available. These were then connected with hinges at the rear sides, being movable as in a clamshell. A top layer corresponding to the skin was made of deposited melted gelatine. The negative castings of the ear entrances were made with the help of [Wood's metal](#) and those for the pinnae with the help of gypsum mix. Once assembled, the corresponding positive castings of the ear regions were formed from gelatine. The ear regions made of gypsum were removed from the artificial head and replaced by those "ears" that were in close resemblance to the natural ones. The rubber mass that surrounded each ear canal and extended into each head half was cut so that the membrane of the microphone, when inserted in its correct location, formed an angle corresponding to the one of real tympanic membranes. The microphone membranes made the ear canals air tight. The membrane (diameter 13 mm) was also not much larger than the tympanic membrane. Based on this fact, the microphone dimensions had been selected to be so small. The inner surface of the artificial head was covered with a 1 mm thick lead plate, which served as a screen against electrical interferences. Each head-half had its own preamplifier that followed already known amplifier principles, but for understandable reasons was assembled in a different way. The construction of the artificial head is better illustrated in Fig. 4 than by numerous words.

Both *output amplifiers* were connected with a resistance-capacitance network and placed in the analysis room.

To observe the sound effects at the "ears" at the same time or to photographically record them, two *cathode ray oscilloscopes* were always used in my experiments. They were Cossor tubes, type C. The stands of the oscilloscopes were constructed so that the tubes could be placed very close to each other. This was necessary to allow their recording on the same film.

As the power grid of our institution yielded only DC, we had to produce high voltage AC current using a rotating *double-anchor converter*. A *voltage supply*, which provided the heater, anode, and [Wehnelt cylinder](#) voltages to the two oscilloscopes, was constructed according to the usual principles.

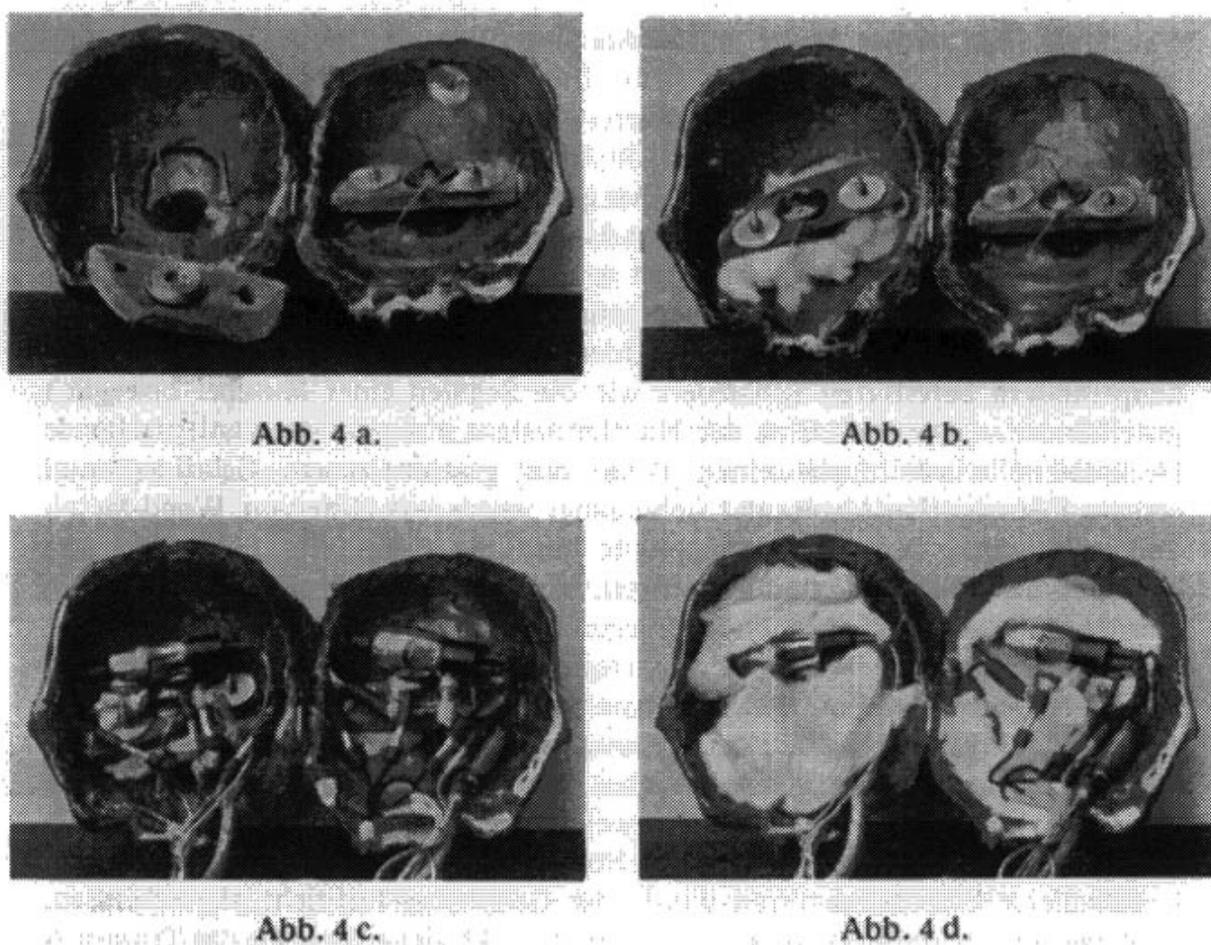


Figure 4: Construction of the artificial head including the preamplifiers. (A higher resolution version of Fig. 4c and the head halves together are shown in Appendix 1.)

An important part of my equipment was the *sawtooth sweep generator*, a known arrangement that is used to deflect the cathode ray beam repetitively with a constant speed. If the beam is deflected by an AC voltage corresponding to the sound signal to be analyzed, the cathode ray draws a figure of the sound process. If the repetitive sweep follows a frequency that corresponds to an integer fraction of the frequency of the sound frequency, then a stationary curve of the tone is shown on the fluorescent screen of the cathode ray tube. For this process, called the synchronization of the sweep frequency, a Pressler gas discharge relay tube was used, which has actually been constructed for other purposes. This tube was found very suitable for my experiments.

The stationary oscilloscope pictures produced in the described way were photographed using a Zeiss-Ikon *movie camera*, model A. The frequency calibration of the sine wave generators and the registration of transient oscillations at onset and offset as well as of the beats and the tone mixtures were made with the running film of an *electrically powered Edelmann camera*.

Between the recording room and analysis room a two-way loudspeaker-telephone connection was provided, which made controlling of the experiments easier.

This was a broad overview of the most important equipment used by myself in the study. Many methodological details are discussed further on in the descriptions of the experiments.

Studies of the external factors effective in directional hearing

Investigations on intensity relations using hearing threshold experiments

It is a physical fact that in a free field sound travels along a linear path. If there are any obstacles in the path, such as a solid object, then there appears behind the object a space where the sound level is lower due to the shadowing effect of the object. The higher the frequency of the sound is, the "deeper" the sound shadow is, and vice versa, the lower the frequency, the less shadowing there is. From this point of view the following experiment is very informative: when we produce a mid-level tone of about 6000-8000 Hz with a loudspeaker and listen to it with one ear closed, then we hear, while rotating the head, the tone most prominent when the open ear faces the sound source. If we then turn 180° so that the open ear is on the opposite side of the loudspeaker, we perceive the sound very weakly, assuming that the room is low enough in reverberation. If we use any small plate as an acoustic mirror — even the palm of the hand is enough here — we can reflect the sound like a light beam to the open ear on the opposite side. This works the better the higher the frequency is. (The 'beam-steering' works at high frequencies, e.g., with ultrasound!) When these experiments are performed with a tone of 200 Hz, the perceived intensity of the sound remains almost constant when we turn a full 360°; also no audible reflection is produced.

If our eardrums were positioned on the surface of our head, then the intensity differences would be primarily due to the shadowing effect. But since our ear canal is about 4 cm long and additionally somewhat curved, the acoustic conditions become complicated, since the sound can never reach the eardrum without diffraction. In addition to diffraction we have to take into account the reflection of sound in the different parts of the pinna and the ear canal; the obvious goal of the external ear is to work as a sound capturing organ. Reflection and diffraction of sound are also always bound together, and in such a way that diffraction is effective at low frequencies and reflection at high frequencies.

In the following investigations I assume that for the same test subject and same frequency the sound intensity corresponding to the hearing threshold remains constant [ref. TRÖGER (1930)]. If we measure the sound level of a loudspeaker at a distance from a test subject, with a level that results in a just noticeable sensation, and let the subject rotate, then the mentioned physical factors will change, and we can obtain a measure for the effect of these factors from the amount of required change of loudspeaker level to maintain the sensation threshold.

Since the number of all possible directions is infinite, I have constrained my studies in such a way that I have determined the intensity differences only in the three main planes, the *horizontal plane*, the *frontal plane*, and the *sagittal (median) plane*. The tones were produced by the sine wave generator and the loudspeaker; the loudness could be adjusted to the order of threshold values using controllable series and parallel resistors without losing the convenient reading of the AC current meter (milliamperemeter with two rectifier tubes). The test subject was sitting on a rotating arm chair in the recording room in the center of a circle, 3 meters in diameter. The circle was divided into 12 sectors of 30° each. The loudspeaker was at the distance of 5 meters from the center of the circle in the direction of the radius marked by 0° and at the height

of the ear of the test subject. One ear of each subject was closed carefully using Ohropax⁴, and after that the determination of the current corresponding to the absolute hearing threshold was carried out in the directions of 0°, 30°, 60°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°. The orientation of the ear to different directions was controlled by rotating the arm chair. The relative hearing threshold was determined at frequencies of 100, 400, 800, 1600, 3200, and 6400 Hz for two test subjects. At least three measurements were performed for each case, and their mean value was calculated.

Table 1: *Relative hearing threshold in different sound source directions at 3200 Hz.*

	mA	relative value
0°	11	1.57
30°	7	1.00
60°	8	1.14
90°	12	1.71
120°	19	2.71
150°	22	3.14
180°	23	3.29
210°	26	3.71
240°	33	4.71
270°	30	4.29
310°	27	3.86
330°	30	4.29

Table 1, which I present as an example, shows the threshold values for test subject N.H. at a frequency of 3200 Hz. The left ear of the subject was closed. The first column indicates the angle, the second one shows the direct reading of the current meter in mA, and the third column is the threshold value scaled so that that the lowest value is 1 and the other ones are in relation to that. This was found necessary in order to express the results of the study in the way shown in Fig. 5. Each investigated direction is shown by its own curve, where the x-axis is the frequency and y-axis is the relative threshold value (indicated as a ratio to the lowest value at that frequency). One can see that the threshold values in the *horizontal plane* are at a minimum on the side and front-side directions of the open ear, whereas the directions symmetric to them show the highest hearing thresholds. One can further notice that the thresholds are raised at frequencies around 200 and 400 Hz only marginally, whereas at high frequencies the absolute thresholds of the contralateral ear are 5-8 times higher than the absolute thresholds of the ipsilateral ear.

The determination of the thresholds in the *frontal plane* was performed in such a way that the test subject was lying supinely on a table-like rack, at one end of which an iron bar was fixed and bent upwards at a right angle. The bar was terminated with a little plate that was covered with a small rubber cushion. This cushion had the role of supporting the head of the test subject. For the determination of the hearing thresholds in different directions the stand was rotated with the test subject so that the head of the subject always remained in the middle point of the circle and the subject's feet drew a circular orbit of 360°. The values determined for the open left ear

⁴A mixture of wax and cotton wool commercially available for such purposes (ear occlusion).

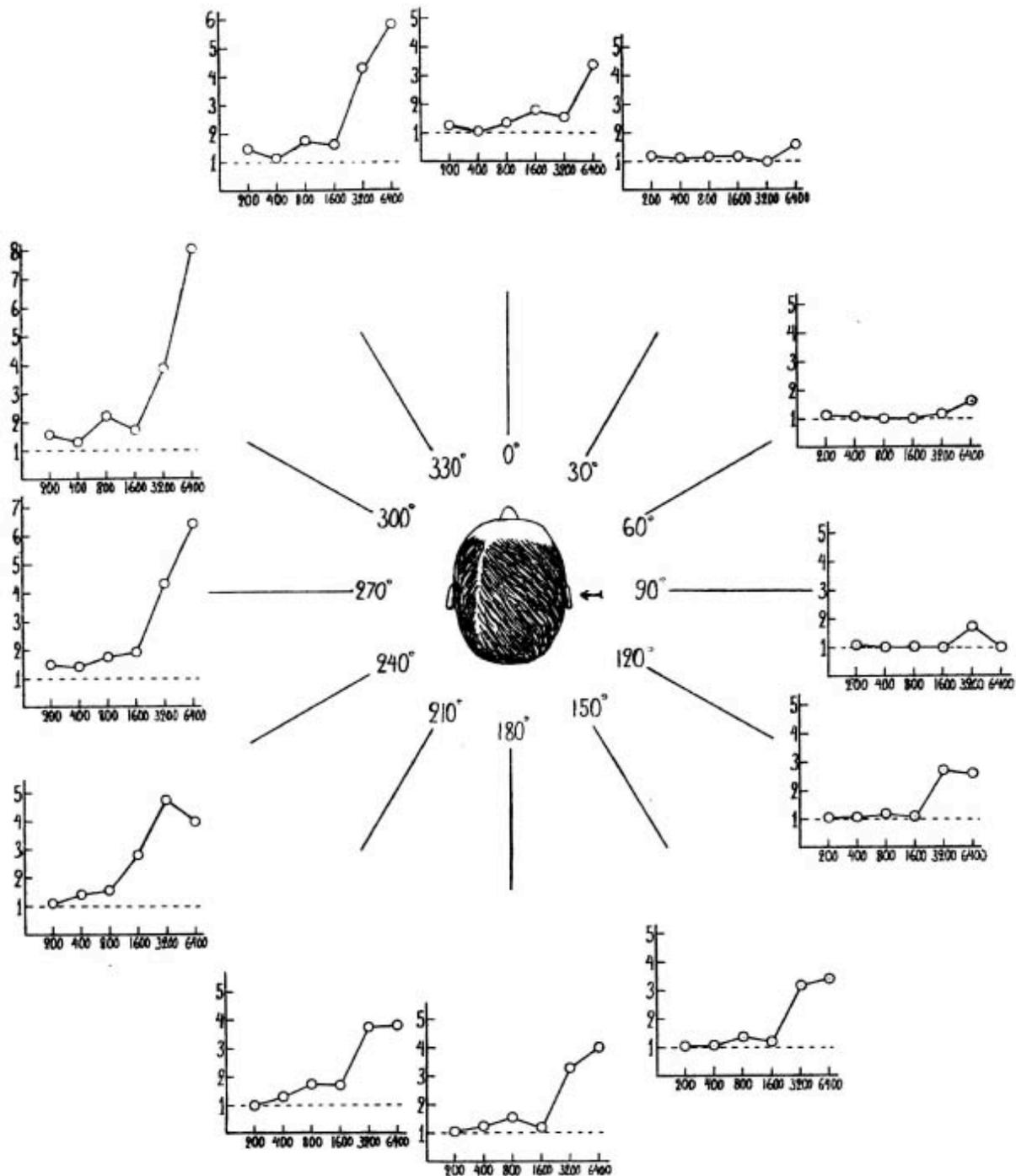


Figure 5: Relative hearing thresholds at different frequencies in the horizontal plane.

can be seen in Fig. 6. One can see that the optimum value for threshold level is in the direction towards the side; otherwise what was said about the horizontal plane is also valid here.

For the studies in the *sagittal* (= *median*) *plane*, the same stand was used as for the frontal plane. The test subject was lying on one side with the closed ear downward and the head on the cushion. From Fig. 7 we can see that variations of the hearing threshold are in general smaller

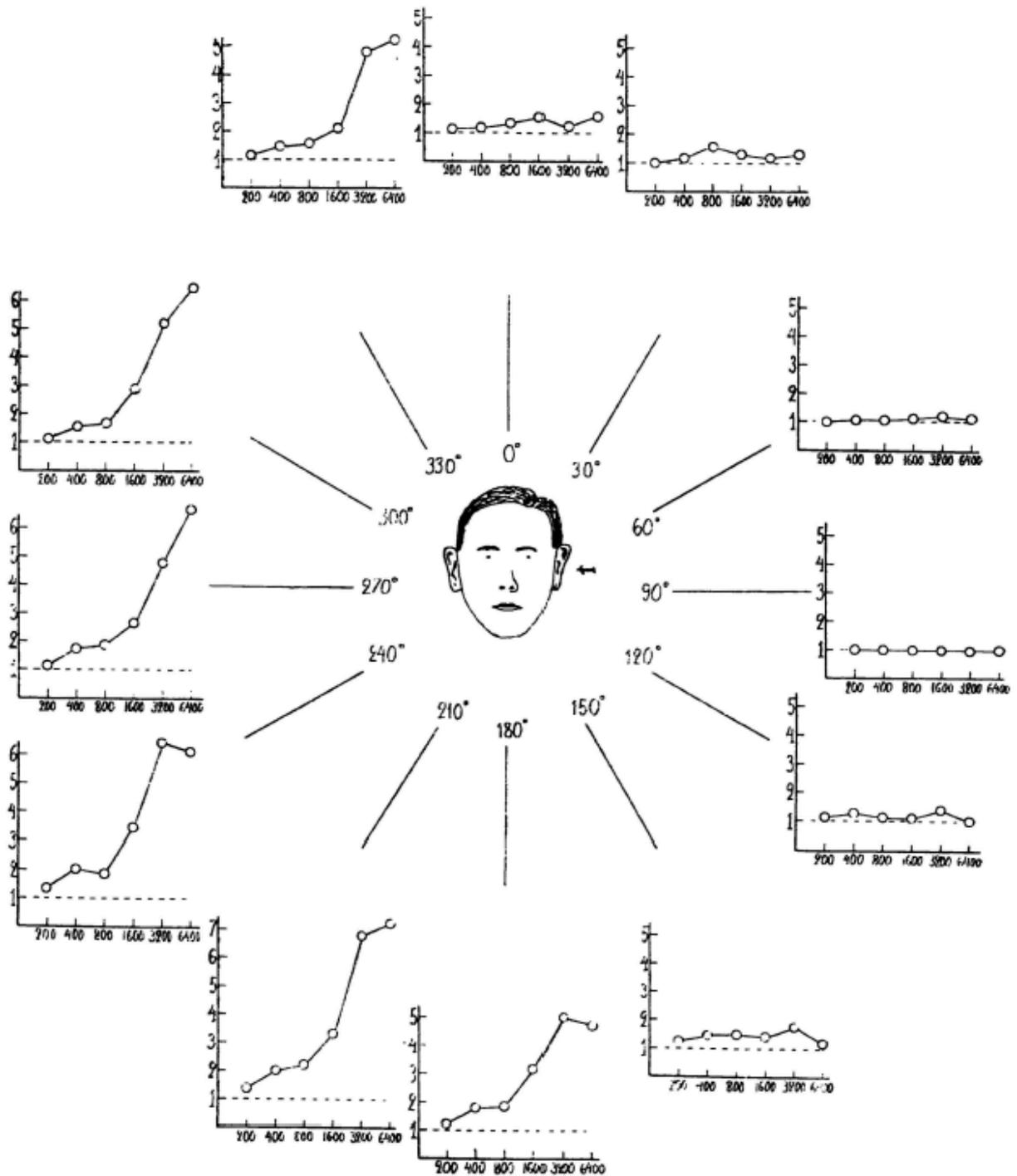


Figure 6: Relative hearing thresholds at different frequencies in the frontal plane.

than in the horizontal and frontal planes. This fact can be explained since the ear canal is at a right angle to the sound direction and the optimal threshold intensity therefore becomes higher than in the horizontal and frontal planes.

The threshold values in Figs. 5, 6, and 7 are for the test subject N.H. (male with normal

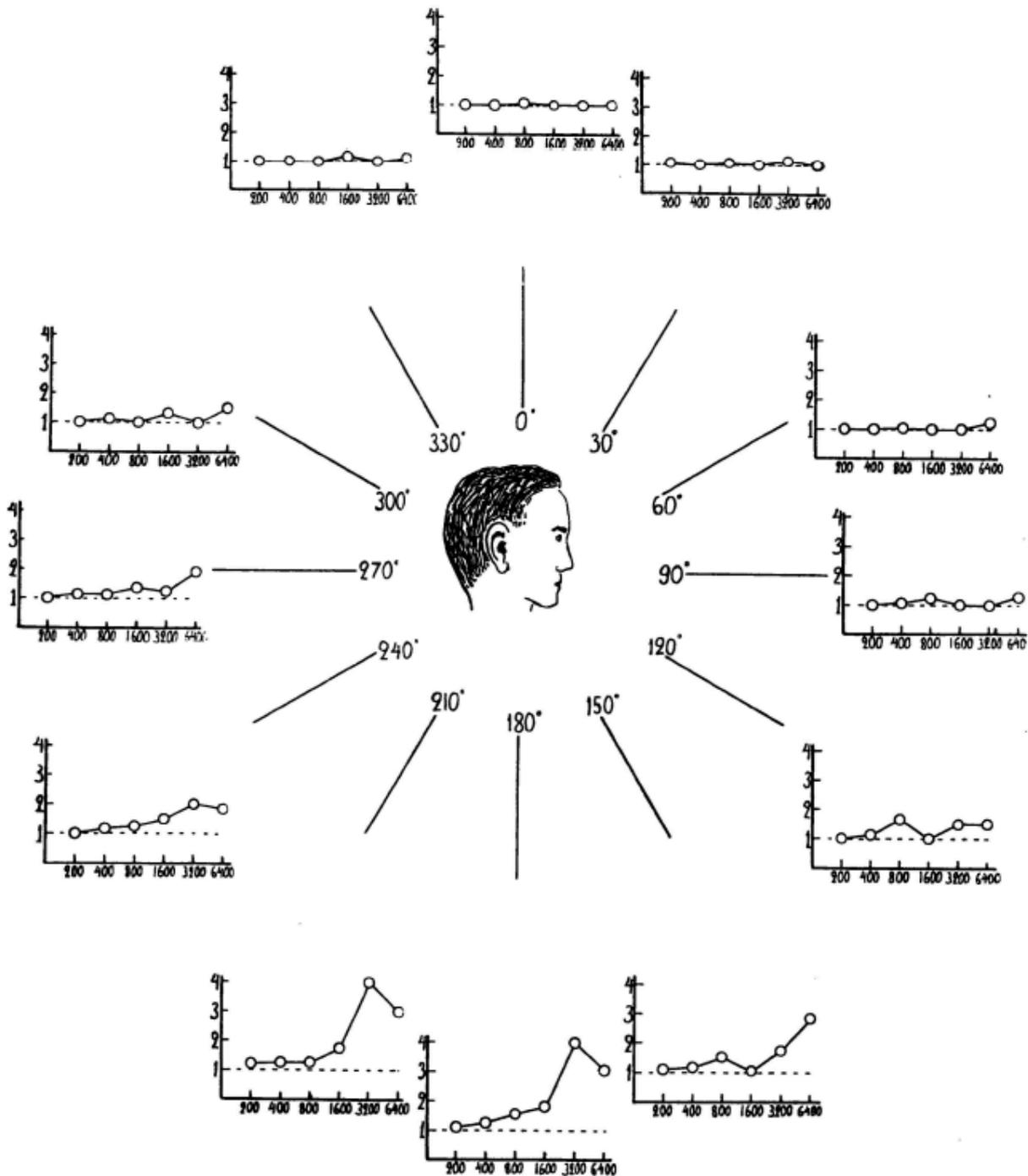


Figure 7: Relative hearing thresholds at different frequencies in the median plane.

hearing, age 21 years). For the second subject, K.V., the obtained values deviate in details significantly from the ones from N.H., however, the overall picture was the same. The differences between the right and left ears, obtained with the same symmetric conditions, were small at low frequencies, while at higher frequencies they were more significant.

If the obtained threshold values in different directions are drawn on a polar diagram in such a

way that the radial distance from the centre is proportional to the absolute intensity threshold for the corresponding direction, an almost circular figure appears at low frequencies when the points are linked together. At higher frequencies the figure becomes the more irregular the higher the frequency is. Most probably this is due to the complex diffraction and reflection conditions at the pinna and the ear canal, effects which appear increasingly stronger at higher frequencies, as we have noticed before. As we will find later in the discussion of these conditions, it is useless to combine the results as mean values from the test series of different subjects, because we will lose the intensity variations corresponding to specific individual anatomical properties, and we obtain a picture of these phenomena that is simple indeed but incorrect [cf. TRÖGER (1930)].

The investigation of external factors in directional hearing other than those concerned with intensity is hardly possible by using subjective methods. In the next section the "electrically hearing" artificial head will be used to explicate these factors.

Artificial head experiments for the investigation of intensity and time differences in directional hearing

If it were possible to register the signals in both ear canals as a response to a sound by oscillographic means, then we could obtain a clear picture, not only of the intensity conditions, but also of the time differences, which appear due to the different distances of the ears to the sound source. With continuous tones these time differences appear as differences in signal phase, and as we recall from the historical overview, many researchers attribute a high significance to these phase differences for localization of sound.

To clarify these conditions, the [artificial head](#) mentioned earlier was constructed. My experimental setup is shown in Fig. 8. Room 1 is the recording room, 2 is the analysis room, and 3 the generator room. The artificial head Ph was in the recording room, hanging 1.5 meters from the floor. The head was connected with flexible cables to the heater and anode batteries on the floor below the head, as well as to the connector board of the recording room. The loudspeaker L was also in the recording room, it was lying on a stand at the same height as the head and being 4 meters from it. The sine-wave generator Sg produced the AC currents as excitation for sound production. Located in the analysis room were both output amplifiers, Ev1 and Ev2; their outputs were connected to the cathode ray oscilloscopes O1 and O2. The sweep generator Ksg produced the vertical movement of both cathode ray beams. The synchronized, equal-phase AC voltages needed for triggering the sweep generator were taken directly from the sine-wave oscillator Sg. When the cathode ray beam was deflected in the horizontal direction by the AC voltage to be analyzed, coming from the vibration of the "eardrum", then a static figure of the sound "heard" by the artificial head appeared on the fluorescent screen of the Brown tube (cathode ray tube). By controlling the sweep frequency, the desired number of vibration periods that were standing on the fluorescent screen could be chosen; the most practical number was 3-6. The standing wave figures of both oscilloscopes were captured on the same film by camera K and then copied to paper by magnification equipment.

Figure 9 presents one experiment performed at the frequency of 3200 Hz. The recordings from the left "ear" are marked by L and those from the right one by R. On the left side, the figure series are given as the rotation angles of the artificial head in relation to the loudspeaker. The first recording was made at an angle of 0°; here the loudspeaker was in the front in the median plane. Then the head was turned 10° to the right, this means clockwise, and a new recording was made, and the process was continued in this way at every 10°. At 90° the loudspeaker was

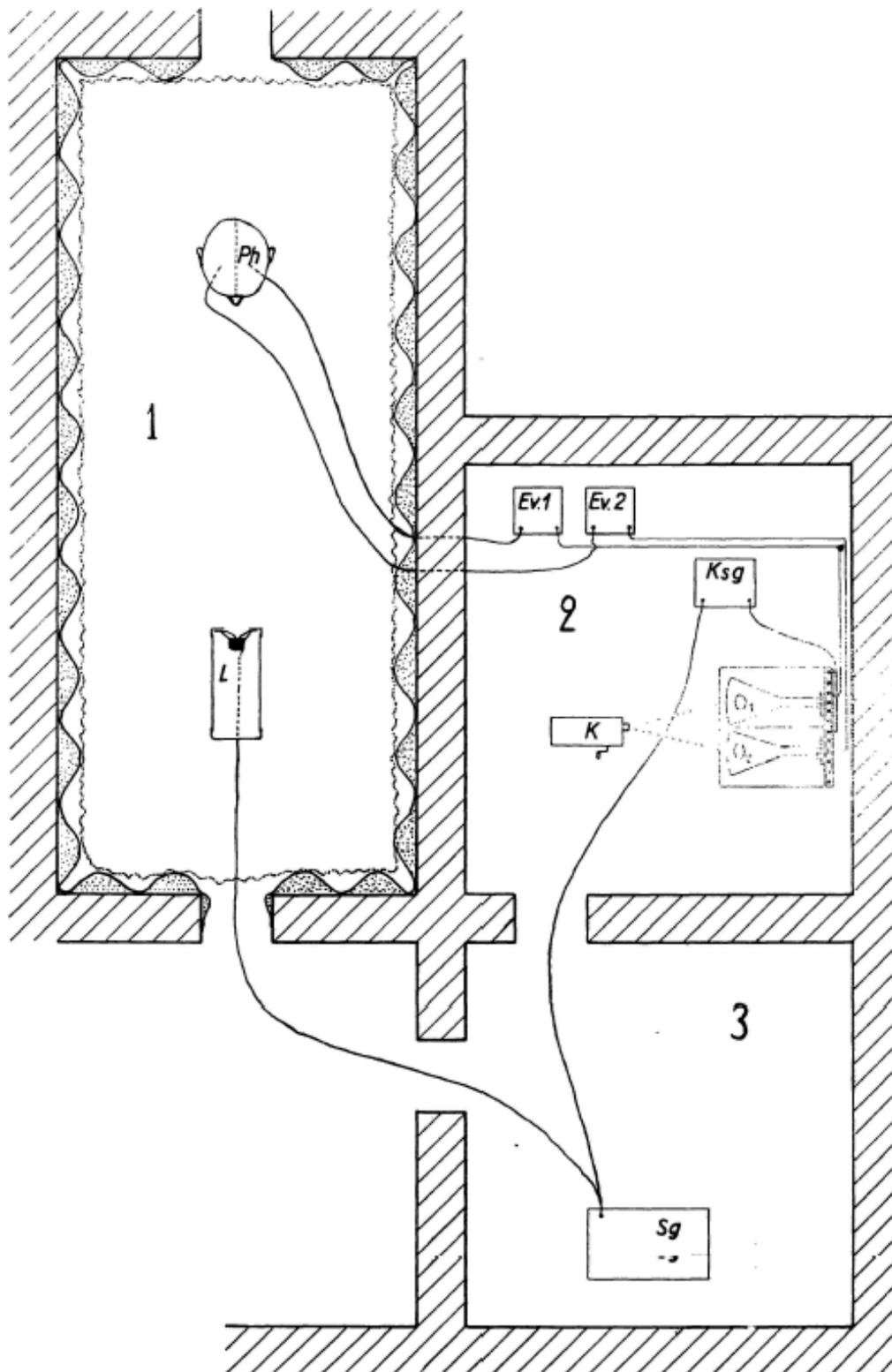


Figure 8: Diagram for the experimental setup with the artificial head.

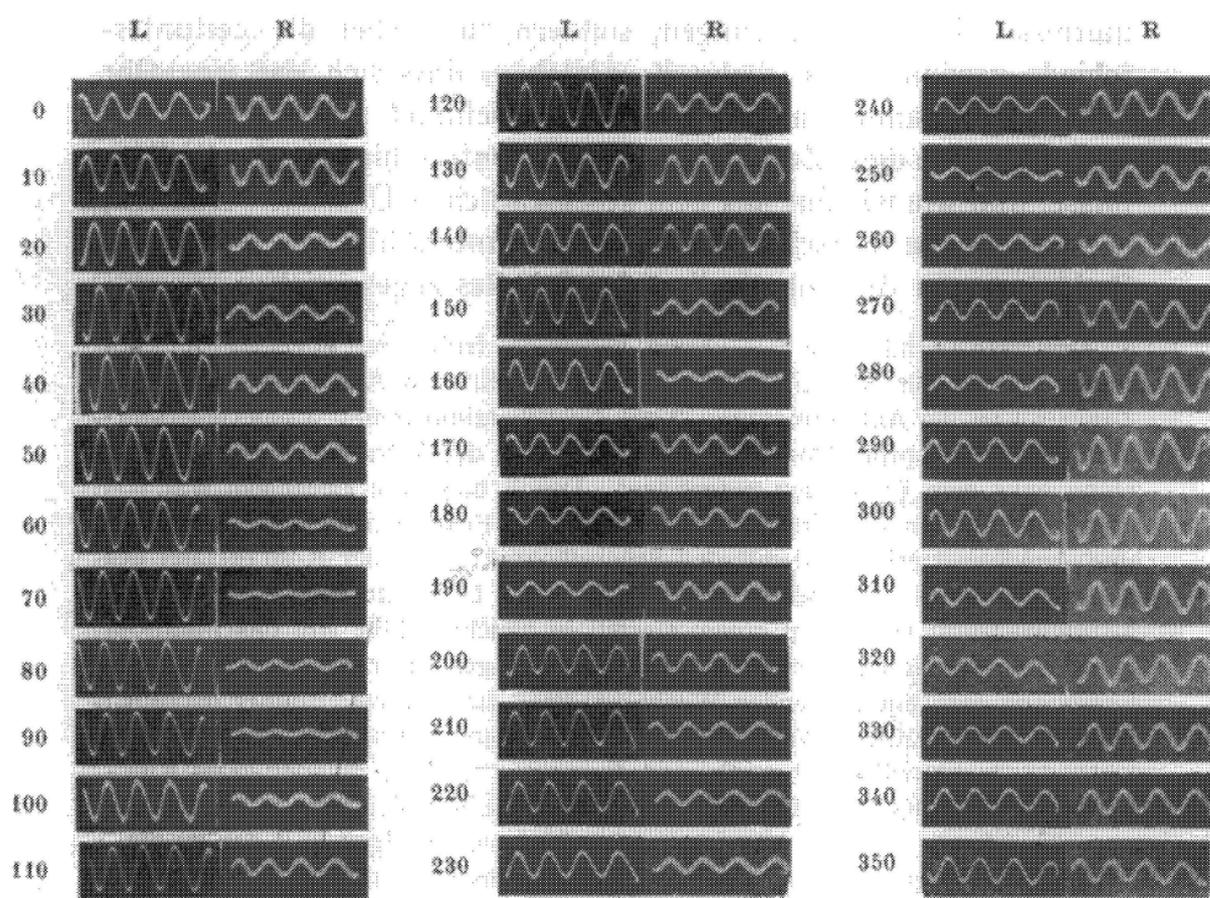


Figure 9: Recordings from right and left "ears" of the artificial head at 3200 Hz in different sound source directions.

on the left side of the interaural line, at 180° to the back in the median plane, and at 270° on the right side of the interaural line.

If we look at the first pair of pictures in Fig. 9, where the loudspeaker was in front of the head in the median plane, we notice that both pictures are quite identical. (The somewhat lower sharpness of the right-hand picture is due to less perfect focusing of the cathode ray beam, which is however meaningless.) When the head is turned to the right, the amplitude at the left side increases, while at the right side it decreases. At 70° – 90° the difference in amplitude is at maximum and for further rotation of the head to the right the amplitude differences decrease. At 150° – 160° we can notice an irregularity, at 180° both curves have the same amplitude, as expected. Between 200° – 230° the amplitude is, contrary to our expectations, on the right side lower than on the left side; from there the tone level on the right side increases. The maximum intensity⁵ difference is found at 280° , and at 350° the intensity balance has already been achieved.

The irregularities that can be found with closer inspection can be explained for the most part by the "anatomical" properties of the artificial head. The form of the head's pinna that was

⁵Translator's note: the author seems to use the terms amplitude and intensity interchangeably. Given that the actually measured quantities are currents, it is most likely that all factors expressed in the various tables refer to amplitude factors.

used as a model was not identical at both sides; likewise the dimensions and curvature of the ear canals were different. It was not purposeful, however, to change this fact. For only very few people is one external ear a real mirror image of the other one; the amount and position of earwax can also vary.

Before we present in more detail the intensity differences at all measured frequencies, we must consider another fact. The reader may already have noticed that the beginning of the curves occurs from time to time at a different position of the wave, this means, at a different *phase*. If we look at the waveforms of 0° and 180° , we see that their starting points have the same phase. This is of course natural since the distance from the ears to the sound source is equivalent in both settings. If we however compare the waveforms from 0° and 10° we find that in the latter case the left ear has reacted earlier in phase and the right ear later in phase compared to the case of 0° . This follows from the fact that the left ear has moved closer to and the right ear farther away from the sound source. This phase difference, which is already more than a full period at 30° , increases until 90° , and then it decreases until 180° , where it becomes 0. With further rotation of the head the phase of the right ear precedes; this phase difference reaches its maximum at 270° , and then decreases, until it disappears at $360^\circ = 0^\circ$, as already mentioned.

If the frequency of a tone is known, then we can determine the time difference in seconds by dividing the phase difference by the frequency. Since the sound velocity in air, as we know, is about 340 meters in a second, we obtain the effective difference of path length in centimeters by multiplying the time difference by 34000. Fig. 10 presents the path length differences at 1600 Hz (mean values from three measurements) and at 3200 Hz (mean values from two measurements) graphically as functions of the arrival angle. At first sight we can recognize the almost sinusoidal form of these curves. From the historical section one recalls the relation proposed by VON HORNBOSTEL and WERTHEIMER (1920): $\sin \varphi = \Delta s/k$ where Δs is the path length difference, φ the rotation angle from the median, and k is an experimentally obtained constant = 21 cm. For a deviation of 90° from the median the path length difference according to the referred authors is $\Delta s_{90^\circ} = k = 21$ cm. As we see from Fig. 10, this maximum path length difference in my study would result in about 24 cm. It must be mentioned, however, that the cadaver head used as a model of the artificial head was exceptionally large. In my view, for heads of normal size the VON HORNBOSTEL-WERTHEIMER constants would be valid.

Let's turn back to *intensity differences*! Table 2 shows the intensity differences measured with the artificial head at frequencies 200, 400, and 800 Hz in angle steps of 30° , and Table 3 shows the intensity differences at frequencies 1600 and 3200 Hz, measured in steps of 10° . In these tables the maximum intensity is marked by 100 and other intensities are per cent compared to the maximum. It appears from the tables that the maximum value (100) is reached in most cases when the sound source is close to the side direction of the ipsilateral ear (left 90° , right 270°). Contrary to that, the ear on the "shadow side" yields its lowest tone amplitude. The lowest amplitude at 200 Hz is for left 93 (right 81), at 400 Hz left 33.5 (36.5), at 800 Hz left 15 (18.5), at 1600 Hz 9 (19), and at 3200 Hz 7.5 (10) per cent at most. It is obvious that at higher frequencies already a change of 10° in direction yields a large variation in intensity of the tone, and that these intensity variations happen often very irregularly. These observations are also in good agreement with the theoretical argumentation (see p. 10) as well as with the determination of the intensity differences based on the hearing threshold, as described earlier. One cannot expect to see an exact correlation between the results from these two principles; it is hardly possible to construct an artificial head resembling the human head in such detail that

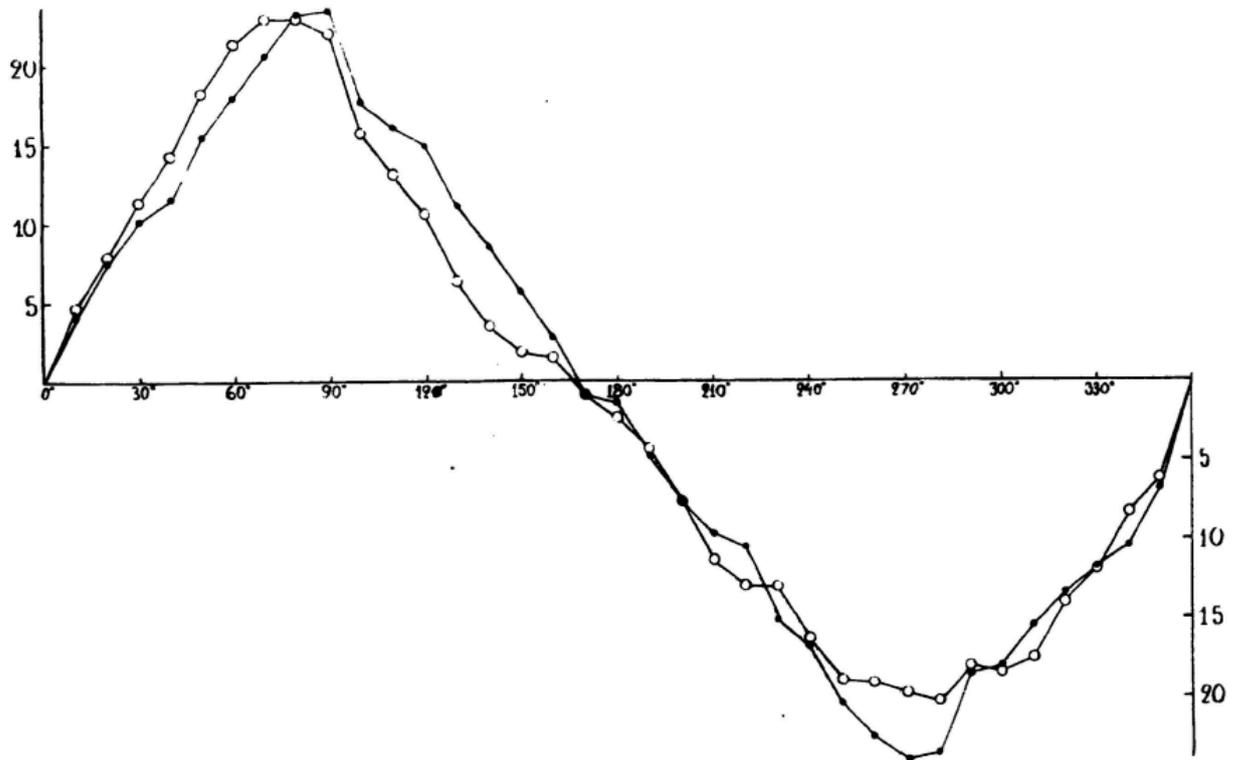


Figure 10: Path length difference as a function of azimuth angle at 1600 Hz (circles) and 3200 Hz as measured with the artificial head.

the artificial one is acoustically entirely equivalent to the human head. Moreover, on p. 14 we have read that even for a single test subject in similar symmetric conditions the values for the right and left ears can be very different especially at high frequencies.

In nature, such pure tones as used, for example, in these studies are hardly ever found; there we are dealing either with tone combinations or with noise. We can imagine how such a complex tone, generally known to consist of a fundamental tone and one or more higher harmonics, affects the ear from different directions. The more the head and the external ear mask the free propagation of sound, including the effect of the shoulders when the sound comes from below, the less the higher overtones contribute to the movements of the ear drum, while the fundamental tone and low order overtones are less affected. This implies that the timbre (sound color)⁶, being dependent on the quantitative relations between the fundamental and the overtones, varies with sound source direction. These differences become stronger as the number of overtones of the sound increases. One can say that a sound which is rich in overtones has a different sound color in each direction of hearing. So we can localize a sound also when listening to it with one ear, assuming that the color of the sound is known in the given direction. The finer our timbre analysis ability is, the more successful the localization can be. Consequently we are justified to speak about *timbre theory* [KLEMM (1920), among others].

⁶Translator's note: it has been difficult to find a consistent use for the terms sound and tone, as well as sound color, tone color, and timbre, taking into account the different detailed meanings of the related words in German and how Wilska is using them.

Table 2: *Intensity differences at frequencies 200, 400, and 800 Hz. Mean values from two measurements at each frequency.*

Angle	200 Hz		400 Hz		800 Hz	
	left	right	left	right	left	right
0°	96.5	81.0	39.5	42.0	58.5	58.0
30°	93.0	90.5	79.5	52.0	82.5	33.0
60°	96.5	94.0	97.5	66.0	100.0	30.5
90°	96.5	90.5	100.0	64.0	82.5	29.0
120°	100.0	81.0	76.5	53.5	80.5	18.5
150°	96.5	81.0	52.0	36.5	69.0	48.5
180°	100.0	81.0	33.5	45.0	54.5	64.5
210°	100.0	87.5	45.5	65.5	35.5	68.5
240°	100.0	94.0	62.0	93.0	25.0	88.0
270°	100.0	100.0	62.0	100.0	23.0	100.0
300°	100.0	96.5	49.5	72.5	15.0	96.0
330°	93.0	96.5	38.5	55.5	22.0	86.0

In binaural hearing, sound localization based on sound color becomes much more accurate than when listening to with one ear only. Now each ear builds its own "sound image" so that we have two cues for the determination of sound source direction. When comparing the sound colors of the right and left ears, from a theoretical viewpoint they are found identical only in the median plane, while in all other directions they are different. To illustrate this, a tone combination of 800 Hz fundamental frequency, a weak second harmonic, and a strong third harmonic was generated by nonlinear amplification made especially for this purpose. This was registered by oscillography in the horizontal plane with the artificial head in the same way as the tones in Fig. 9 (see Fig. 11).

In addition to what was said about timbre differences, it is apparent in Fig. 11 that the phase differences of the overtones, according to their frequency, are larger than those of the fundamental tones. Meanwhile, by closer inspection, one can see here and there smaller deviations from this rule that appear as phase shifts. These can be explained so that the effective distance of the ears ($k = 21$ cm) varies slightly for different frequencies, as is also shown by the calculations of [HARTLEY and FRY \(1921\)](#). The phase shifts, which prove that the path at different frequencies to the eardrum varies in length due to reflections and diffraction, however have no effect on timbre according to [VON HELMHOLTZ \(1913\)](#).

The importance of noise for directional hearing in the light of these results

Noises indicate those sound signals that consist primarily of aperiodic components. We cannot draw a sharp borderline between complex tones and noises, since many noise signals can also contain complex tonal components, and also since many complex tonal signals often have mixed-in aperiodic sounds. By using modern sound analyzers, such as developed for example by [GRÜTZMACHER and MEYER \(1927\)](#), it has become possible to study arbitrary sound signals and to present them in the form of so-called frequency spectra. These frequency spectra

Table 3: *Intensity differences at frequencies 1600 and 3200 Hz.*

Angle	1600 Hz		3200 Hz	
	left	right	left	right
0°	90	56	50	80
10°	90	50	87.5	60
20°	100	30	100	50
30°	100	24	100	24
40°	97	27	100	10
50°	91	30	94	40
60°	81	41	96	44
70°	83	44	100	30
80°	86	41	100	24
90°	90	24	81	18
100°	95	19	69	44
110°	100	44	75	50
120°	95	60	81	32
130°	86	63	81	24
140°	80	68	50	50
150°	72	68	69	36
160°	67	68	81	14
170°	67	68	87.5	30
180°	72	76	81	50
190°	57	80	43.5	50
200°	48	83	50	70
210°	48	94	50	80
220°	33	100	7.5	56
230°	14	100	12.5	40
240°	9	94	25	40
250°	29	94	37.5	50
260°	43	92	37.5	50
270°	43	89	31.5	80
280°	19	89	16	80
290°	24	89	44	90
300°	52	89	37.5	100
310°	62	89	15	100
320°	71	86	19	90
330°	76	86	35	80
340°	86	86	56	60
350°	71	83	62.5	60

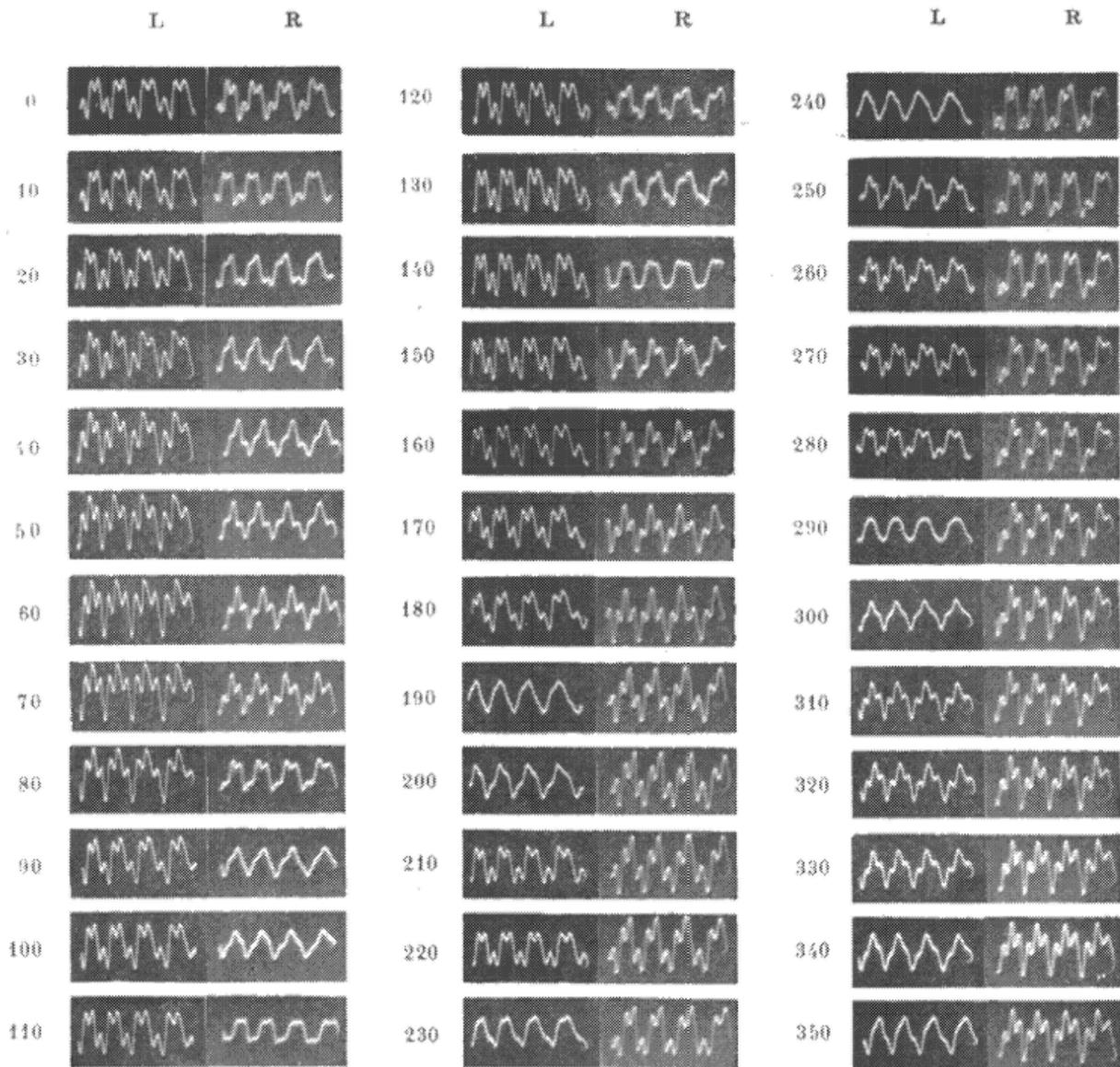


Figure 11: Artificial head recordings from the left and right "ears" using a sound rich in overtones; frequency of 800 Hz.

are curves with frequency on the x-axis, the y-axis being the intensity of each partial tone in the signal under study. The frequency spectrum of a complex tone consists of lines at regular distances on the x-axis, in a way similar to the flame spectra of different chemicals. If any pure noise is analyzed in a similar way, a continuous spectrum will be obtained, the level of which can vary on the y-axis; yet the spectrum is by its continuity different from a tonal spectrum, similarly as a broad color-band of sunlight deviates from spectral lines of certain materials. Just as the sunlight spectrum is composed of spectral lines of different materials, the spectrum of noise consists of innumerable tonal components.

In addition to partial tones, certain sounds exhibit in their spectra also areas of continuous background. These include, for example, the lowest notes of the piano, in which the continuous part of the spectrum comes essentially from the attack of the string vibration ([MEYER and](#)

BUCHMANN 1931). In addition to a continuous background, many noise signals have discrete partial tones that emerge in different resonating parts of the equipment that produce the noise (LÜBCKE, 1934).

At a noisy waterfall, in an express train, or in any other noisy place, one can easily make an experiment that confirms the composition of noise from separate partials. A hand is placed on the ear so that a cavity is created between the hand and the external ear. When only a narrow slit is opened between the hand and the cheek-bone region and the volume of the cavity is varied, then we can hear a tonal character of the noise so that the pitch changes according to the size of the slit. With some training a musically inclined person can learn to produce in this way any desired melody. The explanation of this phenomenon is simple: it is only a variable resonator that amplifies those partial frequencies that it is tuned to.

After these considerations we can more closely deal with the directional hearing of noises. If the noise source is in the median plane, then, on the basis of the frequency spectrum, both ears obtain theoretically the same sound image. But when the sound source is displaced toward one side, then the spectra at both ears change in such a way that the spectrum level is increased at the ipsilateral ear especially at high frequencies, while at the opposite ear a corresponding decrease of level occurs: Our directional hearing of noise signals, based on the difference in sound color, deviates from directional hearing of complex tonal signals mainly because in the former case during the assessment of source direction the smallest nuances in sound color are also perceived, because the noise spectrum, as mentioned, is continuous. We can also see that in this respect noise must be the easiest of all sounds to localize.

Due to this the intensity theory loses its meaning, being limited to pure tones that almost never occur in nature, and I suggest it be renamed *sound color theory* [The term "timbre theory" (see p. 19) relates literally to complex tonal sounds only (see also the footnote, p. 19)].

When listening to a continuous complex tone, its perfect temporal continuity makes it an apparent fact that this monotonic content remains invariant over its span. It is difficult to understand how we could in such conditions obtain a clear perception of path length differences based on the phase differences. The significance of phase differences decreases also since above 800 Hz they become ambiguous and beyond 1600 Hz they are meaningless (see p. 5). The optimal frequency region of hearing sensitivity begins just above this frequency (WIEN, 1903, WILSKA, 1935). This optimal frequency range includes most of the sound effects that we hear: the main part of noise components, the formants of most speech sounds, an important part of sounds from musical instruments, as well as sounds produced by most animals. It would contradict the principle of purposefulness if the frequencies that correspond to the most acute hearing sensitivity and richest excitation would have no meaning in directional hearing.

One can see that the phase theory cannot explain the directional hearing of these most important sounds. Nor is the localization of continuous tones or tone complexes explained by the temporal theory, since they are continuous as mentioned. With noise the situation is different. Noise in its pure form contains nothing periodic, monotonous, rather it is all the time in variation, full of temporal discontinuity. If a noise source exists outside the median plane, then each discontinuity produces a "time stamp" of the effective path length difference between the ears. Since the number of these "time stamps" is high, the difference perception based on them becomes more accurate as the discontinuities become sharper, that is, the higher partial frequencies the noise contains. Following these theoretical argumentations we have to assume that noises are a prominent element of our directional hearing.

Studies on the resolution of directional hearing

General aspects

Before I start describing the research methods that I used, I would like to refer briefly to some methods used earlier by other authors. I will divide these methods into two main groups, indirect and direct ones. These two groups are separated so that in the first one sounds are transferred to the ear through a tube, microphone, headphone etc., while in the second one the sound path is free, as occurring in natural conditions.

In the first group, telescopic tubes are certainly the oldest and most often used instruments. In their classical form they resemble the rubber tube sound endoscope (stethoscope), for which one branch can be lengthened or shortened as in a telescope. In this way, differences in path length and intensity between the ears are created. The ear pieces have also been replaced with a microphone and a headphone, and so the phase and intensity differences can be varied independently; the former one by the telescopic tube and the latter one by controlling the sound level in the headphones, for example, by using potentiometers. The sounds used in the study can be produced by mechanical or electrical means. In headphone listening, the time differences in natural listening can be imitated in such a way that an instrument capable of generating two current pulses in a very short and variable time interval is used to produce a short current pulse, first in one, and then in the other headphone driver (c.f. [KLEMM 1920](#)). Artificial, controllable time differences can also be produced by the [telegraphon](#) by [POULSEN](#) with two magnetic pickup heads, the distance of which is controllable, and which are connected to corresponding headphone drivers.

In the *direct* research method the sound is fed to the ears neither through tubes nor through electric headphones, but the head is located in a free sound field. For successful experimentation it is however necessary that the nearest neighborhood is acoustically maximally "neutral" so that disturbing reflections are eliminated as much as possible. In free open space the acoustic conditions are most favorable. The low directional resolution threshold values ($1/3^\circ$) by [W. and H. MARX \(1921\)](#) are likely to be explained by the fact that the authors carried out their experiments in free field conditions.

When we investigate the directional hearing resolution by physiological experimentation, the test subject can express his judgement of the perceived sound direction in any manner. According to their experimental setup and reasoning, researchers have in the past used different methods. One such widely applied method of investigation is where the test subject estimates on which side of a reference plane (median, frontal, or horizontal) the sound source appears. In many studies the test subject points to the source direction using his finger or a pointing stick. In addition there are methods in which the sound source direction is indicated by optical markers or image schemata ([ALLERS and SCHMIEDEK 1924](#)). Also the task has been to indicate the direction in degrees to a basic reference direction, to split certain angles into halves, etc. ([HOLT-HANSCH 1931](#)).

One cannot deny that the mentioned research methods can be very valuable in solving many special problems in directional hearing. They are, however, not particularly applicable to the determination of directional hearing resolution. If we allow a test subject to estimate which side of the middle line a sound is perceived to arrive from, then it is not easy for the person to conceive accurately where his subjective median plane lies. Owing to this inaccuracy the

entire experiment is problematic. If we let the subject to point to the direction of the sound source, the sense of place of the subject will be taken into account, and similar circumstances apply to optical pointing and to drawing image schemata. Based on their studies, [ALLERS and SCHMIEDEK \(1924\)](#) are of the opinion that the optical and kinesthetic spaces don't fully match, and that the connection between optical space conception and sound impression is not identical with the connection between the latter one and the kinesthetic space conception. [GOLDSTEIN and ROSENTHAL-VEIT \(1926\)](#) have found that in acoustical localization the best results are obtained with test subjects that have inadequate or almost no visual imagination, and that for subjects with good optical ability the results in non-optical methods are better than when using optical methods. The same should, in my opinion, also be valid when the test subjects are required to produce estimates of the direction of sound incidence in terms of degrees. The geometry with which they are optically and possibly [proprioceptively-haptically](#) familiarized is not required to correspond absolutely to the sound source localization geometry. The clarity of a memory image employing conventional units such as degrees for angles can vary widely for different test subjects.

It would be strange if we could study the visual resolution in common situations in such a way that we allow the test subject to estimate if an optical point exists to the left or right of median plane, or permit the subject to indicate a point, as we do when we wish to know if a cataract patient can project the light. The selected research methods are too coarse to determine the visual resolution of a normal eye. While we can also say that the directional hearing resolution is lower than that of the visual sense, the difference accounts only for somewhat more than one order of magnitude, as will be seen later.

In vision as well as in binaural hearing we receive perceptions by projecting the objects of the external world in relation to ourselves by means of the waves emitted from them. The circumstance that our optical projection is obtained through a huge number of single elements, while in acoustic perception we can manage with only two isolated receivers, is based on the fact that in the first case each receptor occupies its own spatial position so that the projection is of a more primary nature, while in the latter case the projection appears only secondarily, on the basis of time and sound color differences.

In many cases we have an incorrect view regarding directional hearing since we see it as a function corresponding to binocular vision. This manner of thinking is certainly anatomically but not physiologically correct. The main function of binocular vision is distance localization, while binaural hearing in the first place mediates only the egocentric directional localization, in the same way as in non-stereoscopic, monocular vision. Therefore, we are allowed to use similar methods from visual resolution studies in the determination of directional hearing resolution.

We know that the visual resolution is defined by the smallest angle for which two optical points can still be separated. Correspondingly, in the determination of directional hearing resolution, we have to select two acoustic points as observation objects, e.g., two small-sized sound-producing objects that are controllable by their distance. Due to the nature of the hearing sense it is favorable to present the sound stimuli *successively*, since in simultaneous presentation, especially with periodic sounds, one can easily interfere with another. If the angular distance between the two sound sources is very small, both directional percepts are merged together; if the distance is then gradually increased, the smallest angle can be found for which both directions can be separated. The threshold value of directional hearing is measured and uniquely defined by this angle.

Determination of directional hearing threshold using impulse noise

Impulsive noise, produced by closing and opening an electric circuit, was used as the excitation. The circuit consisted of the loudspeakers described above (see p. 7) and a 12 Volt battery. The closing and opening of the circuit was accomplished by a switching device, resembling a [telegraph key](#), with which one could produce current pulses in arbitrary order, first to one and then to the other loudspeaker. The loudspeakers were on a stand, 6 meters from the test subject, who was sitting on a round chair. The angle of the loudspeaker direction regarding the test subject was directly readable from a scale, drawn on the stand. If the angle became so large that the width of the stand was not sufficient (for angles $> 15^\circ$), the stand with the loudspeakers could be moved to a distance of 2 meters from the subject, and for these shorter distances the stand had special measurement scales. The positioning of the loudspeaker was performed by an assistant; the leader of the experiment used the circuit switch and registered the results.

At the beginning of an experiment the test subject was seated on the chair so that the loudspeakers were directly in front of him. The angle was selected to be so large that it was easy for the subject to discriminate the two sound directions. For consistency the subject was asked to state *if he heard the last click to the right or left of the first click*, and this task was accomplished by pointing to the corresponding side by hand. Since the test subject could not see the very small movements of the loudspeaker membrane, and since the switching circuit was outside his visual field, it was not necessary to cover his eyes. Therefore, the entire experiment was much more comfortable than some of the experiments described later on, in which it was obligatory to cover the eyes of the subject due to another kind of stimulus arrangement.

After the test subject was somewhat familiarized with the experimental setup, the sound sources were shifted slightly towards each other so that their mid points were at an angle of about 1° from the test subject. As a rule, the subjects were not capable of indicating the direction difference of the sound stimuli anymore but instead had an impression that they emanated from the same place. The angular distance was gradually increased until the test subject was able to localize them without error, and this angle was registered as the threshold angle. Then the test subject was rotated 30° to the right and the threshold angle was determined in the same manner as before. This threshold angle was now regularly somewhat larger than in the 0° setting. Next, the experiments were performed at 60° where the threshold appeared to be even higher. At the sideways setting (90°) the determination was noted as being most difficult since the number of erroneous decisions was much higher than in the other directions where the subject in most cases made correct or uncertain decisions, and more rarely wrong judgments. This fact, that first surprised me, will find its natural explanation later (p. 42). Next, the thresholds were determined at 120° , 150° , and 180° . In the last mentioned setting the sound sources were directly behind the subject, and the threshold values were in general of the same order as measured at the 0° setting. Then the thresholds were determined further for angle settings of 210° , 240° , 270° , 300° , and 330° , and these values corresponded approximately to the values obtained from the other, symmetric side. In this manner, an idea of the distribution of the resolution in directional hearing was obtained for the *horizontal plane*.

The more frequently these experiments were carried out with the same subject, the smaller the threshold values became. This fact is in agreement with the observations of [KLEMM \(1920\)](#) and [HALVERSON \(1922\)](#) about the influence of training in a directional hearing experiment.

All the experiments discussed in this chapter were carried out with two test subjects. Often,

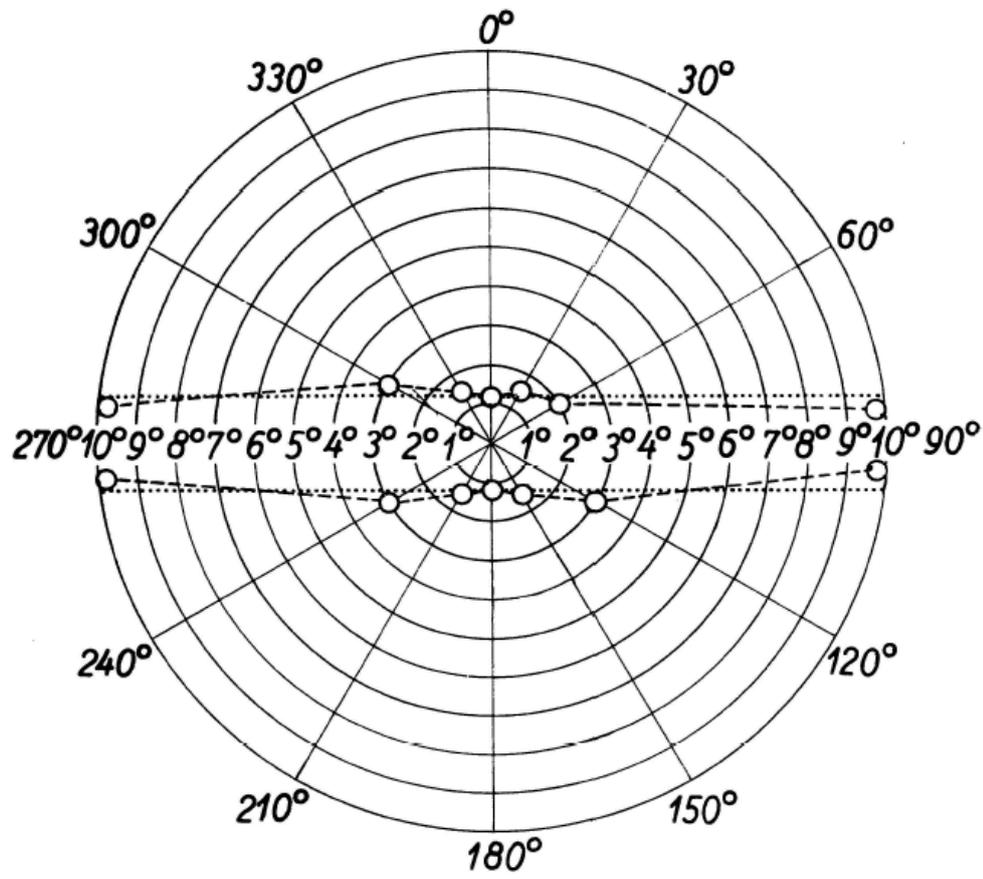


Figure 12: Threshold angle of directional hearing in the horizontal plane using impulsive noise.

especially when something particularly interesting was observed, I took the place of the test subject in order to verify if the measured values were valid in my case. These tests were however not performed regularly, and so the values obtained from myself will not be considered here.

In one experiment with test subject K.V. (after a short training; measurement accuracy 0.5°), the following angles were obtained for his directional hearing threshold: $0^\circ-2^\circ$, $30^\circ-3^\circ$, $60^\circ-4^\circ$, $90^\circ-16^\circ$, $120^\circ-4^\circ$, $150^\circ-3^\circ$, $180^\circ-3^\circ$, $210^\circ-3^\circ$, $240^\circ-4^\circ$, $270^\circ-20^\circ$, $300^\circ-7^\circ$, $330^\circ-4^\circ$.

The corresponding, somewhat lower values obtained for test subject N.H. (after a longer training period; measurement accuracy 0.2°) are shown in Fig. 12. The different radii indicate the angular setting of the test subject in relation to the sound sources, and the radial distance of each circle from the mid point is a relative measure of the threshold angle in this direction. We see that at the directly in front and back directions the threshold angle amounts to 1.2° only. At a 30° deviation from the median direction the threshold is about 1.5° in all four settings in question (30° , 150° , 210° , 330°), at a 60° deviation from the median plane (60° , 120° , 240° , 300°) it is about $2-3^\circ$, while at both side directions (90° , 270°) it amounts to $10-11^\circ$. Due to the reasons explained on page 42 of this thesis and also since in both experiments at the side directions only one loudspeaker was on the interaural axis (axis going through the ears), the last-mentioned thresholds should be presented correctly not only by one point but rather with two points that deviate by one half of the threshold angle from the interaural axis. Therefore, the figure is left open at both side directions.

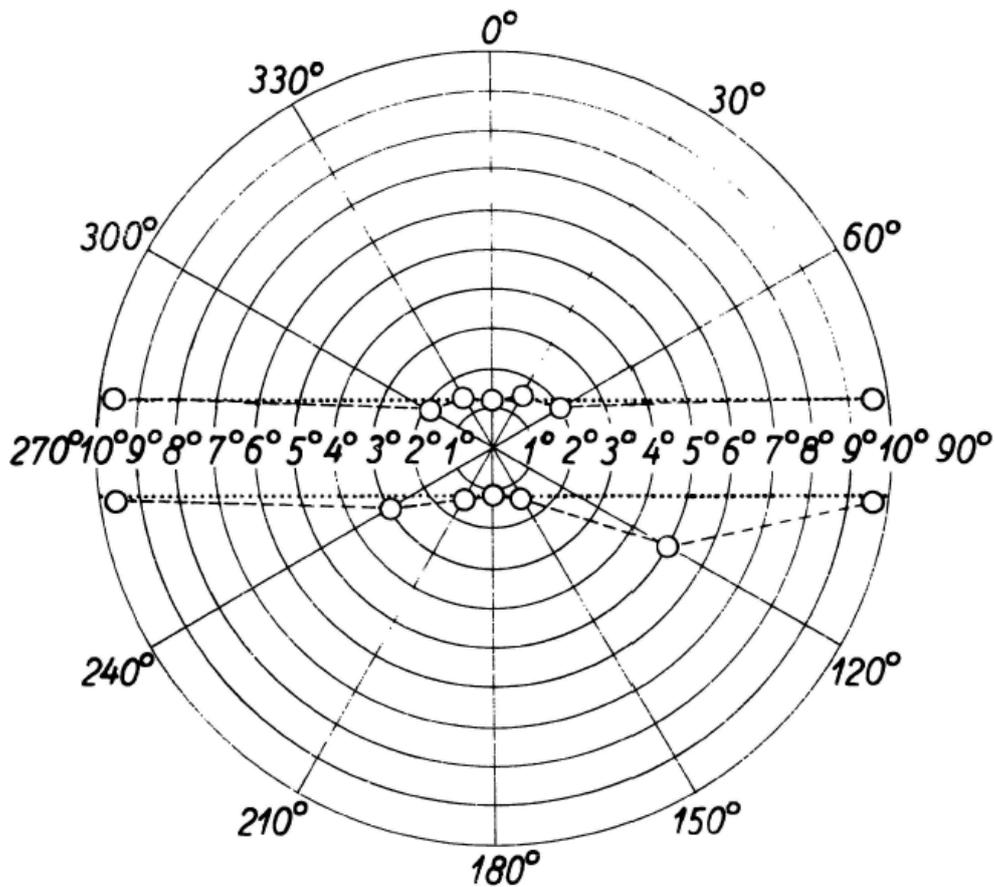


Figure 13: Threshold angle of directional hearing in the frontal plane using impulsive noise.

Corresponding experiments were also conducted in the *frontal plane*, whereby the same table-like stand was used as in the hearing threshold experiments (p. 11). As an advantage of this experiment setup it should be noticed that the threshold angle can be measured also in the directions that in normal conditions are right above the head (0°) and below the feet (180°).

The following results were obtained for test subject K.V. (after a short training period, measurement accuracy 0.5°): $0^\circ-2^\circ$, $30^\circ-4^\circ$, $60^\circ-5^\circ$, $90^\circ-20^\circ$, $120^\circ-7^\circ$, $150^\circ-4^\circ$, $180^\circ-1^\circ$, $210^\circ-2^\circ$, $240^\circ-3^\circ$, $270^\circ-17^\circ$, $300^\circ-10^\circ$, $330^\circ-4^\circ$.

The corresponding values for test subject N.H. are given in Fig. 13, drawn according to the same principle as above.

It was also attempted to use this method to determine the directional hearing thresholds in the *median plane*. I noticed soon, however, as expected, that the threshold angles were very large ($> 30^\circ$) and indeterminate, so that the method was found unsuitable for the purpose.

Let us now look at Figs. 12 and 13 which, as already mentioned, represent the directional hearing resolution measured in degrees in the horizontal and frontal planes. We will notice at the first sight that the threshold values in the "corresponding" directions in both planes match remarkably well. It is self-evident that this uniformity of threshold values has to be based on some sort of similarity in the excitation formation. Concerning the horizontal and frontal planes, both are perpendicular to the median plain. The directions 90° and 270° that are on the

interaural axis are common for both planes. From the point of view of the test subject, for both planes the directions 30°, 150°, 210°, and 330° each deviated by 30° from the median plane, and correspondingly the directions 60°, 120°, 240°, and 300° each by 60°.

Now we will consider the obtained results from the *temporal theory* point of view of. The similarity of the threshold values in the horizontal and frontal planes would be consistent with this theory as the time difference is dependent only on the angle between the sound's incident direction and the median plane, but not dependent on the plane in which the sound source is located. We know from above that the path length difference is:

$$\Delta s = k \sin(\alpha) \quad (1)$$

where α is the angle from the median plane and $k = 21$ cm (see p. 5). If the path length difference is expressed in centimeters, then the time difference is $\Delta t = \Delta s/34000$ seconds, when the sound velocity is 34000 cm/s.

Let us assume that a distant sound source moves with a constant angular velocity from the median plane ($= 0^\circ$) to the direction of 90° on a circle around the mid point of a test subject's head. At an arbitrary angle α the path length difference is also equal to $k \sin(\alpha)$. The growth rate of the path length difference follows the differential equation:

$$\frac{ds}{dt} = \cos(\alpha) \quad (2)$$

and the angle distance corresponding to path length growth difference follows the equation:

$$\frac{dt}{ds} = \sec(\alpha) \quad (3)$$

Let us assume that equally large differences (τ) are required for the effective time values ($\Delta t_1, \Delta t_2$) of the first and second sound excitation to create a threshold perception of directional difference, independently of the base direction, and that it doesn't matter which one is larger, that is, $\Delta t_1 - \Delta t_2 = \pm\tau$, whereby the sign of τ can be omitted as being meaningless. If the first threshold angle, limited to the median direction, is equal to α_0 , then the absolute value of τ from Equation (1) is:

$$\tau = \frac{21 \sin \alpha_0}{34000} = 0.00062 \sin(\alpha_0) \text{ sec.}$$

The *threshold angle β of directional hearing* in the median direction is, as said above, equal to α_0 . It increases with increasing base angle α according to Formula (3), as follows:

$$\beta = \alpha_0 \sec(\alpha) \quad (4)$$

When looking at Figs. 12 and 13 we can see that the threshold angle in the median direction is about 1.2° . If we thus set $\alpha_0 = 1.2^\circ$, then both dotted lines present graphically the values of β as computed from Formula (4). It can easily be observed that the empirically determined values, drawn by circles and dashed lines, are very close to the theoretical values. In my opinion this agreement of theory and empirical findings is a beautiful proof of the validity of the temporal theory.

The number of independent directions that can be discriminated in a quadrant (e.g., 0° – 90°) is obtained from equation:

$$n = \operatorname{cosec}(\alpha_0) \quad (5)$$

Proof. According to the assumption that all values of τ are equal and since the (total) time differences in the 90° direction is equal to $k \cdot \sin(90^\circ)/34000 = k/34000 = n \cdot \tau$, so we obtain: $n \cdot k \sin(\alpha_0)/34000 = k/34000 \rightarrow n = 1/\sin(\alpha_0) = \operatorname{cosec}(\alpha_0)$.

Therefore, it can be assumed that *within a spatial angle* α , constrained by one side at the median plane, for $\alpha < 90^\circ$, there are $n \sin(\alpha) = \sin(\alpha) \operatorname{cosec}(\alpha_0) = \sin(\alpha)/\sin(\alpha_0)$ differentiable directions. Hence (since $\sin 30^\circ = 1/2$) it also follows that, of all the distinct directions, one half belong to the median sector of 30° .

Fig. 14 illustrates the number of just discriminable directions when $\alpha_0 = 1.2^\circ$. According to Formula (5) we obtain $n = 47.75$. Thus, it is possible for a test subject, having a directional hearing resolution of 1.2° in the median plane, to distinguish between approximately 48 directions in the range of 0° to 90° , of which about 24 are on the median sector of 30° .

As can be expected also theoretically, directional hearing appears to be, based on these experiments, almost as accurate in the horizontal as in the frontal plane. This is contrary to the observations of [AGGAZZOTTI \(1921\)](#) who acknowledges sound localization being good only in the horizontal plane.

We will come back once more to these questions later (p. 42).

Experiments with unilateral ear closure

In these experiments, conducted in the same manner as the previous ones, one ear canal was closed carefully with [Ohropax](#). The results (test subject N.H.) are shown in the following table (the values in Figs. 12 and 13 for binaural listening are also shown for comparison here; at 270° the plugged ear is facing the sound source):

Table 4:

Incidence angle	Horizontal plane		Frontal plane	
	Binaural	One ear closed	Binaural	One ear closed
0°	1.2°	5°	1.2°	6°
30°	1.5°	8°	1.5°	8°
60°	2°	8°	2°	18°
90°	10°	20°	15°	18°
120°	3°	24°	5°	14°
150°	1.5°	14°	1.5°	14°
180°	1.2°	8°	1.2°	7°
210°	1.5°	8°	1.5°	10°
240°	3°	24°	3°	35°
270°	11°	48°	15°	48°
300°	3°	18°	2°	30°
330°	1.5°	12°	1.5°	8°

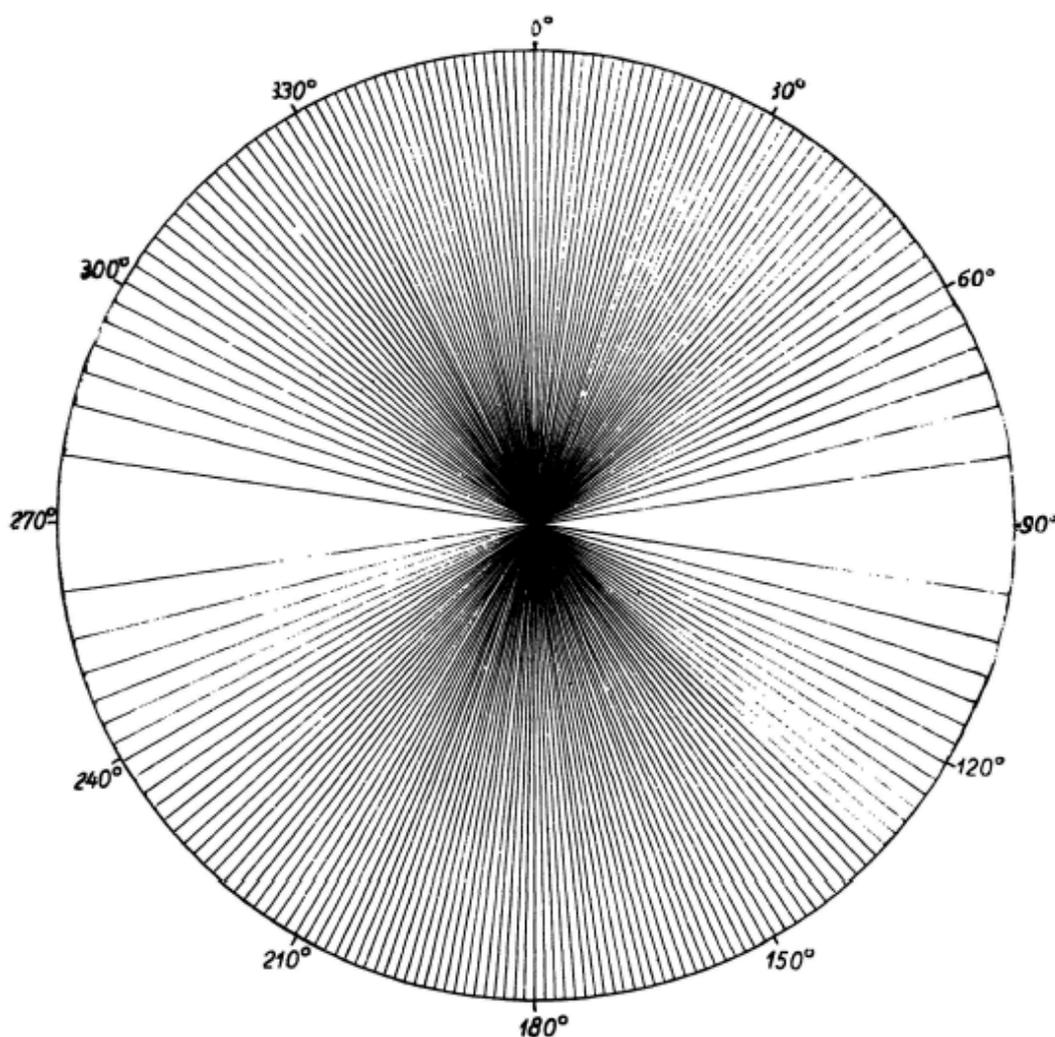


Figure 14: The distribution of just noticeable hearing directions according to Equation 5 (threshold angle in the median plane direction is 1.2°).

From the table we can see that the unilateral ear closure caused a significant lowering of directional hearing resolution mostly at the directions towards the side of the closed ear. However, such an ear closure never eliminates the auditory function of the closed ear completely, and despite all measures taken, especially low frequencies continue to penetrate the ear so that the binaural effect is not entirely eliminated. One can also notice that the lowest thresholds exist directly at the front and back for those columns that present the threshold angle for unilateral listening, while the threshold angles in the direction of the better hearing ear are 3-4 times larger than the former ones. Only a residual of binaural hearing could explain this fact. This assumption is also supported by observations of [PEREKALIN \(1930\)](#), after which the unilateral ear closure affects localization more strongly as the effectiveness of the closure is increased. From the studies by [RAUCH \(1922\)](#) it is known that a unilaterally deaf person almost always exhibits incorrect localization. It can therefore be shown that there is no significant monotic sound localization. These results are therefore in conflict with those from [BRUNZLOW \(p. 1\)](#) who regards monotonic sound localization as an element of our directional hearing.

On the effect of "pulse sharpness"

Attempts were made with test subject N.H. in the context of the studies described on page 26 in order to determine to what extent the directional hearing resolution of pulsed noise is dependent on the "sharpness" of the pulses. By connecting in parallel a $0.05 \mu\text{F}$ capacitor in the speaker circuit, the sound color of the pulsed noise, as a result of smoothing the current pulses, became darker and somewhat weaker; by increasing the battery voltage the pulse was set to approximately the same intensity level as in the earlier experiments. It appeared that threshold angles were about 50-60% larger than those measured with sharp pulses. This observation confirmed the assumption made on page 23 about the importance of the higher noise components as "time markers" in direction judgment.

On the effect of onset and offset time

Some researchers (LACHMUND 1921, PEREKALIN 1930 among others) have found that in experiments with tones the onsets and offsets are important, and that with steady-state tones the direction can not be specified at all or is indicated almost always incorrectly. Since so far no studies exist on the influence of the onset and offset time to the resolution of directional hearing, it was found necessary to take a closer look at this aspect.

Let us first consider what events happen at the beginning and end of a sound signal. It is largely dependent on the nature of the sound source, with which speed the tone amplitude grows from 0 up to a certain value and then is brought down to 0, i.e., how short the onset and offset times of this system are. Sound sources that are in resonance with the sound produced by them (most musical instruments, pipes, etc.), have a relatively long onset and offset time. With externally controlled systems, for example the loudspeaker, it is different, provided that their eigenfrequency is not close to the applied frequencies. Such systems can achieve almost instantaneous onset and offset responses since they must obey "slavishly" the electrical impulses given to them. If we apply sinusoidal AC current as a source of sound energy, then by closing and opening the circuit we can achieve an extremely steep fade-in and fade-out of sound.

It would be very interesting to investigate, to what extent the onset and offset rates have effect on the directional hearing resolution. We can arrange for an electrically generated tone with a certain onset and offset rate by connecting a variable resistor in the loudspeaker circuit. For slow processes, one could use a mechanically rotary resistor or a potentiometer; but since we are most interested in faster onset and offset processes, we must use a device that functions automatically and without sluggishness.

As such a device, I have used the electron tube. It is known that the internal resistance of such a tube depends on the grid voltage. If the grid voltage = 0, there exists between the anode and cathode a constant resistance, dependent on the design data of the tube, but when the grid voltage is gradually changed to the negative direction, the resistance in the anode circuit increases until for a certain negative voltage the resistance = ∞ .

The negative value of the grid voltage is brought about by loading a capacitor, connected between the cathode and the grid, from a battery and through a resistor. The larger the resistance or the capacitance, the more time passes until the grid is made sufficiently negative, and the slower the resistance increase in the anode circuit becomes. If the capacitor is discharged through the resistor, the negativity of the grid vanishes at a rate that depends on the values of the capacitance and the resistance.

This is the case when a DC voltage is coupled between the anode and cathode. As known, the anode current flows only in one direction so that with AC voltages, only one half-cycle can flow through the tube. But because the sound becomes quite distorted, it is advantageous to obtain both half-cycles, and to that end I have series-connected a battery of 120 volts in the anode circuit, i.e., a voltage source that gives a bias current, which the alternating currents can overlay. In the lower part of the tube characteristics the sine wave of the alternating current is somewhat nonlinearly distorted. This distortion can be avoided by a complex circuit, but since my experiments were only qualitative, I have avoided it.

The closing and opening of the grid voltage battery was accomplished by an electrically driven connector, which had been adapted from a rotary circuit breaker of LAPICQUE (made by BOULITTE). After its closing, the grid capacitor was loaded through a series resistor; after opening it was discharged through a parallel resistor. These resistances have been calculated so that the onset and offset times were the same. The contact circuit included also a switch that alternately coupled one or the other loudspeaker in the anode circuit during the "quiet" interval, i.e., at full negative charge on the grid capacitor. The test subject then felt like the sound swelled up in one speaker, remained stationary and faded out, and then repeated after a short pause in the other speaker. The determination of the threshold angle was carried out in the usual manner; it was just the angle α_0 that was determined (= directional hearing threshold angle in the median plane). The period of transition from one speaker to another was 3 seconds. The calibration of different capacitors corresponding to onset and offset times was carried out by oscillograms; the longest onset and offset time was 0.5 seconds.

The results for the test subject N.H. at frequencies 400, 800, 1600, 3200 and 6400 are presented in Table 5 as follows.

Table 5:

Onset/offset time	Frequency/Hz				
	400	800	1600	3200	6400
Threshold angle					
0.0000 sec	1.5°	1.5°	1.8°	1.6°	1.5°
0.0005 sec	1.5°	1.8°	2.0°	2.0°	3.0°
0.001 sec	1.8°	2.0°	3.0°	2.5°	3.0°
0.0025 sec	2.0°	2.5°	5.0°	3.5°	4.0°
0.005 sec	2.5°	3.0°	10.0°	5.0°	6.0°
0.01 sec	3.0°	3.5°	12.0°	8.0°	9.0°
0.025 sec	3.0°	5.0°	12.0°	8.0°	9.0°
0.05 sec	4.0°	5.0°	14.0°	13.0°	10.0°
0.1 sec	5.0°	5.0°	16.0°	14.0°	14.0°
0.25 sec	7.0°	7.0°	24.0°	16.0°	16.0°
0.5 sec	14.0°	8.0°	25.0°	24.0°	20.0°

From the table we see that if the onset and offset times increase approximately logarithmically, the directional hearing thresholds grow nearly linearly. Due to the imperfections of my methodology, I do not feel justified to draw any further conclusions from these results, since the nonlinear distortion in this experimental arrangement can have a considerable influence on the results.

I mentioned earlier that for sound localization based on time differences we need temporal discontinuities in the stimulus sound, and that our direction estimation becomes more accurate as the sharpness of these discontinuities increases. Most prominent is, of course, a fast on- or off-switching of the sound. The slower the on- and off-switching occurs, the more blurred these "time markers" are and the higher the threshold becomes. Sudden switching on and off also creates an impulse sound, whose strength and aperiodicity increase as the rate of the on- and off-switching processes increases. Such aperiodic acoustic stimuli (i.e., containing a broad frequency band) are also interesting from the standpoint of sound color theory. Even in the electrical processes of the cochlea and the auditory nerve, corresponding on- and off-switching effects can be identified, as appears from the investigations of [DAVIS and his co-workers \(1934\)](#); this will be described in detail later.

Directional hearing experiments with tone mixtures

Tone mixtures arise, for example, from the simultaneous action of two or more AC currents of different frequencies reproduced on the same speaker. If both of the two simultaneously acting alternating currents are nearly sinusoidal, beating results whose frequency is equal to the frequency difference of the two primary AC currents. These beats can be heard in the loudspeaker separately only to a certain upper frequency limit that is dependent on the nature of the primary tones; if the frequency difference is greater than about 100 Hz, then an objectively non-existent tone of the height of this frequency difference, the so-called difference tone, becomes audible. Naturally, we can also hear both primary tones.

Two sinusoidal current generators were used to produce AC currents that could then be mixed in any ratios by two potentiometers and fed into in the anode circuit of tube resistance as discussed in the previous chapter. The function of the switching device was the same as in the previous chapter. Only the threshold angle α_0 (= directional hearing threshold angle in the median plane) was determined in this experiment.

First, experiments were carried out at the frequencies of 900 and 1500 Hz. Both frequencies were oscillographically controlled so that their amplitudes were approximately equal. The difference tone with a frequency of 600 Hz was clearly audible. Directional hearing thresholds were determined with on- and off-switching times ranging from 0 to 0.5 seconds. The threshold angle proved to be independent of these conditions and was always about 1.5° (with variations of 0.3°). With each primary tone, control experiments were also performed with an on- and off-switching time of 0.25 seconds; the threshold for 900 Hz was 10° and for 1500 Hz it was 8° (see Table 5, p. 33).

Similarly, the interaction of the 1900 and 2500 Hz frequencies was examined. In such a tone mixture the average value of threshold became 1.9° , regardless of the on- and off-switching times (variation of individual values was 0.3°). When the on- and off-switching time was 0.25 seconds, the threshold for the primary tone of 1900 Hz was at 8.5° and for 2500 Hz it was 11° .

From these results one can see that *the threshold angles of both tone mixtures themselves are so small that the on- and off-switching processes do not play a role anymore*. This is easy to understand, however, if one knows that such a superposition of two tones of different frequencies produces continuous amplitude variations, and the fade-in and fade-out occur so often per second as indicated by the frequency of the difference in tone.

From these first-time studies that have not been reported in the literature before, the remark-

able fact appears that the directional hearing threshold angle in a tone mixture is small, despite the illusory continuity of the sound stimulus. I believe that a systematic investigation of these circumstances would bring to light many important results regarding directional hearing for this particular class of stimuli that have as of yet been studied only relatively little.

Directional hearing experiments with continuous noises

Continuous noises were generated by amplification of the "inherent noise" of a carbon microphone, which was located in a soundproof room. The noise that the speakers produced in this manner was very uniform, whizzing like a waterfall, or as the safety valve of a boiler. The noise was directed alternately to each speaker with an onset and offset time of 1 second using the connector device described earlier, and the threshold angle was determined in a similar manner as in the previous experiments.

The angle threshold of directional hearing α_0 (in the median plane) was 1.5° for subject N.H. and 1.2° for another test subject. These low thresholds are a striking proof of the validity of the ideas listed on page 23 about the importance of *temporal discontinuities* in noise for directional hearing. It can be stated here that *when you hear such a noise, the directional information is almost more prominent than the actual sound content, while listening to a tone complex the directional information is weak, while the sound content instead appears strongly.*

Directional hearing experiments with continuous tones

We can see from Table 5, where the effect of the onset and offset time on directional hearing of tones was presented, that the threshold angle is large (up to 25°) with extended onset and offset times. As has already been mentioned, these attempts should be regarded only as qualitative. But it would be interesting to know how large the threshold angles are for continuous tones, being fed to the loudspeakers as freely as possible from overtones and nonlinear distortion. For this purpose, the sounds were "cleaned" with a three-stage octave filter and alternately fed to each individual loudspeaker through two $10000\ \Omega$ Lewcos-potentiometers⁷. The potentiometers were turned in this experiment so slowly, that both the onset and the offset times were about 2 seconds. These experiments were conducted at frequencies of 400, 800, 1600, 3200, and 6400 Hz and in the directions of 0° , 90° , 180° , and 270° of the horizontal plane. It was found that the threshold angle varied for both subjects (N.H. and K.V.) and for all tested frequencies between 25° and 35° ; in the directions 0° and 180° they were in general smaller (25° - 30°) than in the directions of 90° and 270° (30° - 35°).

Since localization in these experiments is possible only on the basis of phase and intensity differences, it is clear from these large threshold values that these factors cannot in general play a major role in sound localization. Looking at these factors separately, the phase differences can come into play only at the two first frequencies (see p. 3). For the other frequencies, the obtained imprecise localization is possible only by intensity differences.

Experiments on the significance of phase differences in directional hearing

Under natural conditions, phase differences always occur together with intensity differences. Artificially it is possible, however, to obtain the former alone, for example, by using telescopic

⁷London Electric Wire Co & Smiths

tubes, beating tuning forks, or electrical oscillating circuits. In my experiments I used the latter two methods. I will first describe the experiments carried out using electrical methods.

Two sine wave generators were tuned to the same frequency. Each output circuit was connected by frequency filters and potentiometers to one headphone. It was ensured that the headphones were connected the same way, i.e., that the same current changes also resulted in the same membrane movements. The output circuits were also connected to cathode ray oscilloscopes, and the common simultaneous "sweeping" of the cathode rays was achieved by the sweep generator that received its synchronization from a single sine wave generator. If the frequencies of the two sinusoidal currents were exactly the same, a standing sine wave curve appeared on the fluorescent screens of both oscilloscopes. If the generators were somewhat detuned, a standing wave would appear on that tube that synchronized the sweep generator, while the figure on the other tube was winding either forwards or backwards, depending on whether the frequency of one side was higher or lower than the other side. At a certain moment the two figures had the same phase; then gradually the phase difference grew to 180° , in order to decrease down to 0° again. With the aid of the potentiometers, the volumes of the two headphones were brought to the same loudness level by successive comparisons. The phase differences that one could see on the oscilloscopes also existed between the headphones. One could easily convince himself of this by placing both headphones on a table and noticing how the tone produced jointly by both headphones appears strongest when the same phase is observed on the oscilloscope, while the tone fades with increasing phase difference and disappears completely at a phase angle of 180° .

If the headphones with the continuous phase change are placed on the ears, the beating disappears completely. Also, when detuning increases even further, so that the phase shifts occur quickly, one cannot hear any beats, except in the case where the tone's volume is made very strong. The emerging, very vaguely audible beats depend mostly on the influence of tissue (bone) conduction.

Out of three observers I was the only one who could hear any localization effects due to the phase differences. The other two subjects indicated that they found the tone uniform and equally strong at both ears without any shifts from one side to another. The entire frequency range of 200 to 2000 Hz was investigated, but the result always remained the same. I myself was able to perceive a very vague "turning tone sensation" in the frequency range of 200-1200 Hz. A movie camera was ready to "fix" the phase relationships corresponding to the sensations of different directions, but it soon turned out that it was impossible to define the direction of sound in any way. Also, the number of incorrect decisions between right and left was just as large as those for correct judgments.

Similar results to mine were also reported by [BANISTER \(1925\)](#). His method of investigation has a certain resemblance to mine. He emphasizes that in these experiments a surprising number of erroneous decisions exist between right and left. According to BANISTER, tones up to 1400 Hz can be heard on the basis of phase differences at an unspecified side direction, whereby autosuggestion based on theoretical expectations plays a significant role.

Based on the facts presented above, it should be clear without doubt that *phase differences play no major role in the localization of sound*. But there are investigations, such as [HALVERSON \(1922\)](#), [STEWART \(1922\)](#) and [VALENTINE \(1927\)](#), after which the significance of phase differences in directional hearing became apparent. Then the question arises as to whether the research methods employed by these researchers are indisputable. The electrical tuning forks used by them also produce some harmonic overtones in addition to the fundamental, and fur-

thermore in each period a short noise arises in part due to the mechanical vibration and partly due to electrical sparking in the contact arrangement. These noises can make sound localization essentially easier due to time differences and may explain the regularities found by the authors.

For further support of my point of view I performed the following experiments: two slowly beating ordinary tuning forks of C^1 (= 258.6 Hz) were placed, one on each side, about 0.5 meters from the ears on the interaural axis. In this arrangement, each test subject could hear a tone moving alternately from one side to the other side ("a rotating tone"). This was, however, not based on the phase difference alone but in this experimental arrangement, where a tuning fork located on one side can also influence the other ear, a small intensity difference appears, the direction of which varies in time with the beat frequency. On the other hand, if the resonating boxes of the beating tuning forks were placed with their open ends on the ears so that the pinnae were partly located within the boxes, then each fork projected its effect almost exclusively onto its own ear. This meant that the just discussed "rotating tone" disappeared completely, although the effect of the phase difference continued unchanged. These latter experiments were carried out with 57 normal subjects (students aged between 20-25 years). Of these, 52 heard neither rotational tones nor dichotic beatings, and the remaining 5 listeners informed me that they had observed a very unclear rotating tone. As the frequency of the tuning forks fell within the optimal range from the standpoint of the phase theory, this result speaks against the importance of phase differences in directional hearing.

Experiments on spatial impression, on the localization accuracy, as well as on the importance of time and intensity differences on binaural-electrical transmission of sound

In preliminary experiments which, as I stated earlier, were executed in the building of the Finnish Radio Broadcasting Company, I focused my attention mainly on the qualitative differences between monaural and binaural sound perception. If we listen, for example, to a broadcast performance in a normal manner with headphones so that both ears receive approximately a similar stimulation, then, although we hear with both ears, we still lack the characteristic differences in sound stimuli between the ears that would occur in natural listening, and the process remains in any case "monaural", lacking spatial effect; we feel it as being "flat" like a picture, that despite the observation with both eyes, lacks the perception of depth that would be the result of disparity between retinal images. The most important "disparity" in directional hearing is the binaural time difference, which can be maintained even in electrical sound transmission by placing two microphones about 21 cm away from each other and having each microphone connected to a corresponding headphone driver. Although the resulting "binaural" effect cannot completely replace the one occurring in nature — it obviously lacks the shadowing etc. effects of the head and the outer ears — in this arrangement we can observe the nevertheless quite obvious differences in the nature of monaural and binaural hearing.

For these experiments, two condenser microphones from Telefunken were used, the mutual distance of which could be varied arbitrarily. After amplification, both output circuits were connected to a switching device in such a way that with this device the performances in the studio could be listened to either in the usual way, that is "monaurally", or separated, that is "binaurally", whereby switching from the monaural system to the binaural one was accomplished instantly. With monaural presentation the effect was the same as in ordinary radio listening —

the orchestral music was found to be located inside the head and could not be projected outside. If the system was converted to a binaural one using the switch, an amazing change occurred: the orchestra "spread" around the observer, the music was playing sonorously, and it was easy to distinguish the various musical instruments from each other, and it seemed as if one could focus attention on a single instrument, whereby the other ones were "suppressed". Many musically trained persons (conductors, virtuoso, musicians) were present as listeners in these experiments, and most expressed their amazement of the natural sound image, and they requested that this system would be made generally available in the future.

On the differences between monaural and binaural listening, studies have been performed among others by [VON HORNOSTEL \(1923\)](#), [AGGAZZOTTI \(1929\)](#) and [HARTRIDGE \(1934\)](#). The first author says, quite correctly from my point of view: "Binaural sounds play fuller — not actually louder — than monaural. The former ones have some reverberation that is missing from the latter ones".

It was also interesting to observe that the binaural effect was most natural when the microphone spacing was about 21 cm, according to the von HORNOSTEL-WERTHEIMER constant. For shorter microphone distances the instruments appeared more shifted to the median plane, while for larger distances (> 50 cm), the sensation of excessive echo appeared.

More detailed studies on the *significance of the path lengths (= time differences)* were conducted in the recording room of the Institute of Physiology. The previously described condenser microphones with their tower-like preamplifiers (see p. 7) were used. They stood close together on a glass plate that was placed horizontally on a stand, which was equipped with a millimeter scale. Time differences between the microphones were achieved by moving one microphone forwards and backwards in relation to the other one. The resulting small intensity differences were compensated by potentiometers in the output amplifiers, and optical inspection was carried out by the two cathode ray oscilloscopes. Impulsive noise was applied as sound stimuli, produced in the same manner as in the experiments on p. 26. The test subject, who was in the analysis room, also operated the telegraphic key for generating the stimulus sounds, which were reproduced by the loudspeaker in the recording room. The assistant, who was in the recording room, carried out the movements of the microphones. To do this, he received instructions by telephone communication between the analysis room and the recording room.

The determination of wavelength difference threshold and the corresponding "median" threshold angle α_0 occurred in the following manner. First, the two microphones were placed side by side at an equal distance from the loudspeaker and then an impulse signal was produced. Then the assistant moved one microphone, either forwards or backwards, after which the signal was repeated. If the microphone distance was large enough, the test subject then observed that the last impulse was located on the side of the shorter sound path, where the first pulse marked the median plane. This repeated marking of the median plane for each trial was absolutely necessary since the test subject had difficulties with these small threshold angles whether the sound was to the right or left of the (subjective) median plane (see also p. 24). Based on my tests, I cannot share the view of [HORNOSTEL \(1922\)](#), after which it is easy to find a direction where the sound "just no longer appears to the side". Variations of the subjective median in these experiments were 5-10° for one and the same test subject, where the experiments were arranged so that the assistant slowly moved the microphone back and forth for repeated impulses until the subject reported that he heard the signals in the median plane.

In the experiments, in which I participated as an observer, a *path length difference of 1.1*

cm (average of 10 trials) was obtained. This corresponds to a threshold angle of 3° . Although this value is larger than that obtained with naked ears ($1-1.5^\circ$), it is yet surprisingly small, considering that the *time difference at an angle of 3° is only 0.00003 seconds*. The reproduction of such a small difference in time depends on the accuracy of the sound transmission equipment particularly with regard to high frequency components. Ordinary headphones are very limited in terms of reproducing the entire sound spectrum. At frequencies $> 5\ 000$ Hz their reproduction decreases significantly, and the upper frequency limit is much lower than that of the human ear. Also, the transient effects and various vibration modes in such edge-clamped telephone earpiece membranes, which have been studied for example by [TRENDELENBURG \(1930\)](#), have the effect of deteriorating the sound quality. It might have been possible to obtain smaller threshold angles through the use of piezoelectric headphones or thermophones, which work better at higher frequencies.

I also wanted to investigate, as several previous authors such as [VON HORNBOSTEL and WERTHEIMER \(1920\)](#), [TRIMBLE \(1929\)](#) have done, how much of a larger path length is required for the pulse sounds to be heard purely to the side. We know that it is 21 cm according to [VON HORNBOSTEL and WERTHEIMER \(1920\)](#). With continuous impulses I let the assistants increase the distance of the microphones gradually until the sound migrating from the median plane to the side appeared on the interaural axis. This happened at a path length of about 22 cm (variation range 20.5-24 cm). If the path length increased even further, the sound remained in this direction up to a path length of 45-50 cm. If the path length was increased even further, there appeared, similarly to the observations made by [KLEMM \(1920\)](#), [TRIMBLE \(1929\)](#), a second sound image in the opposite direction, that continued to increase in strength with increasing path length.

In the experiments described in this chapter, I projected the electrically produced sound direction perceptions initially to the frontal half of the horizontal plane. But soon I noticed that the click signals, which appeared in front in the median plane, suddenly "flew to the back". As soon as I freed myself of the idea that the signals should be heard in the horizontal plane, a spontaneous change of direction took place. Not only did the direction change between front and back, but every now and then the sound "flew" up or down, or towards any other direction on the median plane, while the sound stimuli occurred in both ears with no time difference.

The explanation of these facts is simple. In nature, all directions of the median plane are equivalent to each other as far as they correspond to zero time difference. In the absence of a time difference, that is, if the sound signals meet both ears at the same time, we localize the sound in the median plane as in the above-mentioned experiments. Since it would seem unnatural for us to find this sound arriving equally from all directions in the median plane, we "choose" one of these directions. In nature, this choice is often facilitated by additional sensory impressions, but as all these influences have been excluded by the experimental design, the choice here depends only upon random circumstances. One such case is the mentioned prejudice that the sound can be located only in the horizontal plane; another one is the "aversion" in one direction in the absence of factors characterizing this direction. In the optical domain, an analogical "aversion" will appear when you view the well-known staircase or cube figures which lack any perspective information.

This is how it behaves in the median plane. The same is also true for the case where we achieve side localization of sound with a suitable path length difference. If we create, e.g., a 30° deviation from the median plane to the side (in my experiments, six determinations gave

an average of 10.4 cm; the angle was just approximated), then a change of direction occurs for all those directions on this side of the median plane that are forming an angle of 30° with the median plane when viewed from the center of the interaural axis. All these directions are on the surface of a cone whose apex is located in the center of the interaural axis and whose axis coincides with the interaural axis. The greater the path length (= time) difference is, the sharper the cone becomes, and the smaller the area is where the direction change takes place, until the cone collapses to its axis (ear axis) for a path length difference of 21 cm (in my experiments 22 cm). *The interaural axis directions at both sides are therefore the only ones that can be clearly localized due to time differences.* As we know from before, the *directional hearing resolution is at its weakest in these areas.* — These circumstances will be reconsidered in the next chapter.

The effect of the *intensity difference* of sounds fed to both ears was investigated by amplifying sound in one headphone using a potentiometer. If the intensity difference was 3–4-fold, no side localization of sound could be achieved. Only after it was raised to 5–10-fold, the sound was heard on the side of higher intensity, but there was also sound present on the median plane (in the direction that corresponds to the time difference of 0). One could not "project" the former one to the outside, but it appeared as if inside the ear itself. If a smaller time difference was brought about by moving the microphones, it was not possible to compensate the side localization based on time difference by any opposing intensity difference, but it always resulted in a double sound. These results on the effect of the intensity differences are consistent with the observations of [STEWART \(1920\)](#), [LACHMUND \(1921\)](#), [HALVERSON \(1922\)](#) and [TRIMBLE \(1929\)](#).

To make our binaural-electrical listening system *higher in fidelity*, the two microphones were mounted on the artificial head as in the experiments on page 15. Otherwise, the experimental design was the same as that described previously, but with the exception that we determined the *threshold angles of directional hearing* by two loudspeakers in the same manner as in the previously described determination of angular thresholds with *naked ears*. The threshold angle of directional hearing α_0 obtained this way in the median plane was equally about 3° . Experiments on the influence of intensity differences indicated the same results as above (doubling of sound, etc.). Similarly, the same directional change of sound was observed that has been discussed earlier in this chapter. In the middle point the sound intensity of the artificial head was "equalized" by successive comparisons using the headphone circuit, and then the potentiometers were left untouched, to ensure natural intensity differences (= sound color differences). Although the naturalness of sounds heard in this manner was amazing, one could not distinguish whether a person speaking in the recording room was located in the front or back (up and down are naturally not considered here). If the observer turned his head to the side, something unexpected happened: the person speaking was either "carried away" with the movement or projected upward. This phenomenon may well have a natural explanation: head rotation *under normal circumstances* always causes a change in the specific directional hearing features (time difference, sound color difference) except in the case when the sound source is on the axis of rotation; the vestibular and the cochlear portions correspond to each other perfectly, while the vestibular stimulation (head rotation) *in our experiment* has no such cochlear (time and sound color differences) counterpart. It follows that the sound is located either up or down, or is perceived in such a manner as if it is bound to the rotation of the head. The voice of a talking person is usually heard close to the horizontal plane, so the latter alternative will be preferred.

It is remarkable that from these artificial head experiments one can obtain only the azimuth angle of sound, while the precise projection, i.e., the choice between front, rear, top, bottom, etc., is completely absent. One might think that our experience on such localizations was limited to our own head, and that the artificial head reproduces these delicate sound color manifestations to us "in a foreign language." We would underestimate the sound reproduction capabilities of the artificial head if we did not discover later that even when listening with open ears, the time-difference-equivalent directions are often confused.

Experimental studies on the properties of our listening space

The previously discussed investigations relate primarily to factors that cause side localization of sound. However, it is important to know how those directions, that are on the same angular intervals on the side from the median plane, are separated from each other. Only after we have determined the directional resolution of these, so to speak, time difference equivalent directions, we can obtain an impression of the nature of our listening space.

To be able to specify the different directions of the listening space, a spherical frame of 160 cm in diameter was constructed out of a 3 mm thick galvanized iron wire. It consisted of ring-shaped parts, of which the three largest were joined with each other in such a way that they corresponded to the three principal planes (horizontal, frontal, and median plane). Iron wire rings were soldered together at their intersections. On both sides of the ring representing the median plane, slightly smaller rings were attached in such a manner that that, when viewed from the front of the sphere center, they were 30° away from the median ring. In a likewise manner, on both sides of the horizontal ring, rings were installed at a 30° distance. After these, also four smaller rings were soldered in parallel with the last-mentioned ones at a 60° distance from the median and horizontal planes so that the framework (skeleton), which proved to be very stable when finished, was hung using several wires 30 cm above the floor in the recording room. Now the intersecting portions in the lowest part of the construction within the small rings were cut off so that the test subject could crawl inside the framework. The test subject was sitting on a small adjustable chair, and by raising and lowering the chair his head could be adjusted to be located in the middle of the sphere. The frame created no acoustical disadvantages because of the total area of the wires covered only 1.6% of the entire surface accounted for by the sphere. The acoustic stimuli were produced by small "castanets" as they are available in toy shops. The sound-generating part of it consists of a fairly long steel plate. If one presses with a finger on the free end of this piece of sheet metal, then the other slightly inwards curved end suddenly flips up, creating a sharp click. An important advantage of this device is that the sound radiation due to the small size of the noise-producing area (about 1 cm²) is very "point-like", which is a circumstance that becomes important when working with short distances. They are also very easy to use.

Although the main purpose of these experiments, as mentioned, was the investigation of spatial hearing in time-difference-equivalent directions, also the threshold angles of directional hearing in front (0°) and back (180°), in the horizontal plane and upward (0°) in the frontal plane, were determined for each test subject (across 24 subjects). With the 14 subjects first studied the threshold angles were also determined for the directions 30°, 60°, 120°, 150°, 210°, 240°, 300°, and 330° in the horizontal plane and 30°, 60°, 120°, 240°, 300°, and 330° in the frontal plane. The determinations in the directions 150°-210° in the frontal plane have been

omitted since they proved to be difficult to obtain using this experimental arrangement, where the test subject was in a sitting position. Also, the determinations in the interaural directions (90° and 270° in both the horizontal as in the frontal plane) were discarded, since it was difficult for an inexperienced test subject in these directions, and even a trained subject often failed (see p. 23) to give exact answers, obviously for the following reason: if we give, e.g., two sound stimuli in the horizontal plane, one in the 90° direction (to the right on the interaural axis) and the other one at 75° (to the right, a bit to the front), the test subject easily confuses the latter one with the slightly different time-equivalent 105° direction (to the right, a bit to the back) and indicates that the latter one is located further back than the former one, although it is just in the opposite way. The same applies to the frontal plane.

The determinations of directional hearing threshold angles were performed in the following manner: first, there were 2-3 click signals in rapid succession at a given point of the sphere framework, then the experimenter moved the "castanet" to the desired direction where the clicks were repeated. The angular distance between the two click signals was varied in the usual way to get the smallest just noticeable angle, the threshold angle, and the value of this threshold angle was easy to determine using the framework. As averages from the experiments with 14 subjects, the following threshold angles were obtained:

In the horizontal plane: 0° — 2.1° , 30° — 3.1° , 60° — 6.5° , 120° — 7.3° , 150° — 3.6° , 180° — 2.7° , 210° — 3.7° , 240° — 6.8° , 300° — 8.1° , 330° — 3.8°

In the frontal plane: 0° — 2.5° , 30° — 3.8° , 60° — 9.6° , 120° — 11.0° , 240° — 9.8° , 300° — 10.5° , 330° — 3.5° .

One can see that the threshold angles are nearly equal in the median plane in all three places (0° and 180° for the horizontal, 0° for the frontal plane) (variation range 0.6° , mean error 8%). The same also applies to directions that are time-difference-equivalent to a 30° distance from the median plane, i.e., 30° , 150° , 210° , and 330° in the horizontal plane, as well as 30° and 330° in the frontal plane (mean error 5.5%). Larger differences are found between the directions that are time-difference-equivalent to 60° , i.e., 60° , 120° , 240° , and 300° in both planes mentioned, and in a way that the average value of the threshold angle in the frontal plane is about 43% higher than in the horizontal plane. The difference is probably due to the fact that the reflecting effect of the shoulders in these directions of the frontal plane is remarkably disturbing, while it has no greater meaning at the 30° and 330° directions of the frontal plane as well as in all directions of the horizontal plane.

The obtained results support the view of the importance of time differences in side localization of sound as expressed by the formulas on page 29. While we can attach no special significance to these values as a result of the inexperience of the subjects, we must ascertain that the thresholds obtained in the median plane (0° and 180°), are about 25% smaller than those calculated by formula (4) on p. 29, for other angles. This may be due to the fact that in their everyday life the test subjects perform their most accurate sound localization by turning their head, so that the sound source becomes located in the median plane, and as a result of experience, the directional sensitivity is increased at this position. The median plane would therefore constitute a "foveal" zone in the auditory space.

We can definitely say that *the sharpness of directional hearing in the strict sense — i.e., the ability to distinguish which one of two successively presented sounds is closer to the median plane or the lateral direction — follows a simple rule (Formula 4, p. 29), according to which it is most accurate in the median plane and degrades to the side.* That this rule is valid not only

in the horizontal plane and the frontal plane but also applies to all other planes that are parallel to the median plane and intersect each other on the interaural axis, is not only highly plausible but has also been verified by some blind tests.

The majority of investigations so far relate to those directions where the time differences can be decisive for localization. As previously pointed out, only the possible localization of sound to the side can be effected through time difference; however, it is not possible to project the sound source accurately on the time-difference-equivalent cone shell. Are there other clues available for this latter kind of localization, or is our hearing space constituted in such a way that it gives *one* projection with great accuracy, while in another projection we are left in the dark?

Attempts to explain this question were performed with 24 subjects. The same spherical framework was used as above. The "castanet" was attached to one end of an 80 cm long light wooden stick on a rubber pad so that it could be comfortably moved to all points of the framework unnoticed by the test subject and set in function by pulling a string. In each test series, the sound stimuli were given in time-difference-equivalent directions. First, the median plane was examined, and then the time-difference-equivalent directions of 30° to the right, 30° left, 60° right and 60° left. The test subject was informed before each series of tests in which segment the sound stimuli would be presented, and their task was to indicate the sound direction with a small stick. Before each test series, a little bit of training was provided. This experimental arrangement, which is unsuitable for side angle determination due to its inaccuracy, is justified here since its errors are low compared to the large uncertainty of the localization in question here. At all selected points, 2-3 click signals were given in quick succession and the direction in which the test subject responded was registered. With each subject only one attempt was made in each direction.

Figure 15 shows the obtained results in different directions in the median plane. The arrows in each sub-figure indicate the direction of the sound stimulus and the responses of the subjects as points on the circumference. Therefore, the number of points in each figure is that of the subjects, i.e., 24. It can be seen from the figures just how inaccurate the localization of sound is on the median plane. In some sub-figures one can see that in the vicinity of the arrow the points are more or less compressed together, while in others only scant or no proper localization is found. Without compromising the accuracy of the presentation, I have drawn two points side by side when they otherwise would coincide according to the experimental protocol.

Figure 16 presents the studies which were carried out in the time-difference-equivalent directions of 30° to the right (the outer circle) and 30° left (inner circle) from the median plane. The same imperfection of the localization behavior as above is also found here. The same applies to the time-difference-equivalent directions of 60° to the right and 60° left of the median plane; I think that a graphic representation of these results is unnecessary.

After all these experiments, we can say that our auditory space is designed in a very peculiar way. Each perceived sound direction appears in our consciousness as highly "*astigmatic*"; it is sharp in one projection, in the other ones it is ambiguous. This disadvantage, however, occurs only in *static directional hearing*, that is, if the head of the observer remains motionless. By moving the head of the observer the localization of sound is much easier. In the following, I introduce some examples from this topic that I would call *kinetic directional hearing*.

Suppose a person localizes a continuous noise or the like based on his static directional hearing so that he fails to detect the precise sound direction in the median plane. Suddenly he

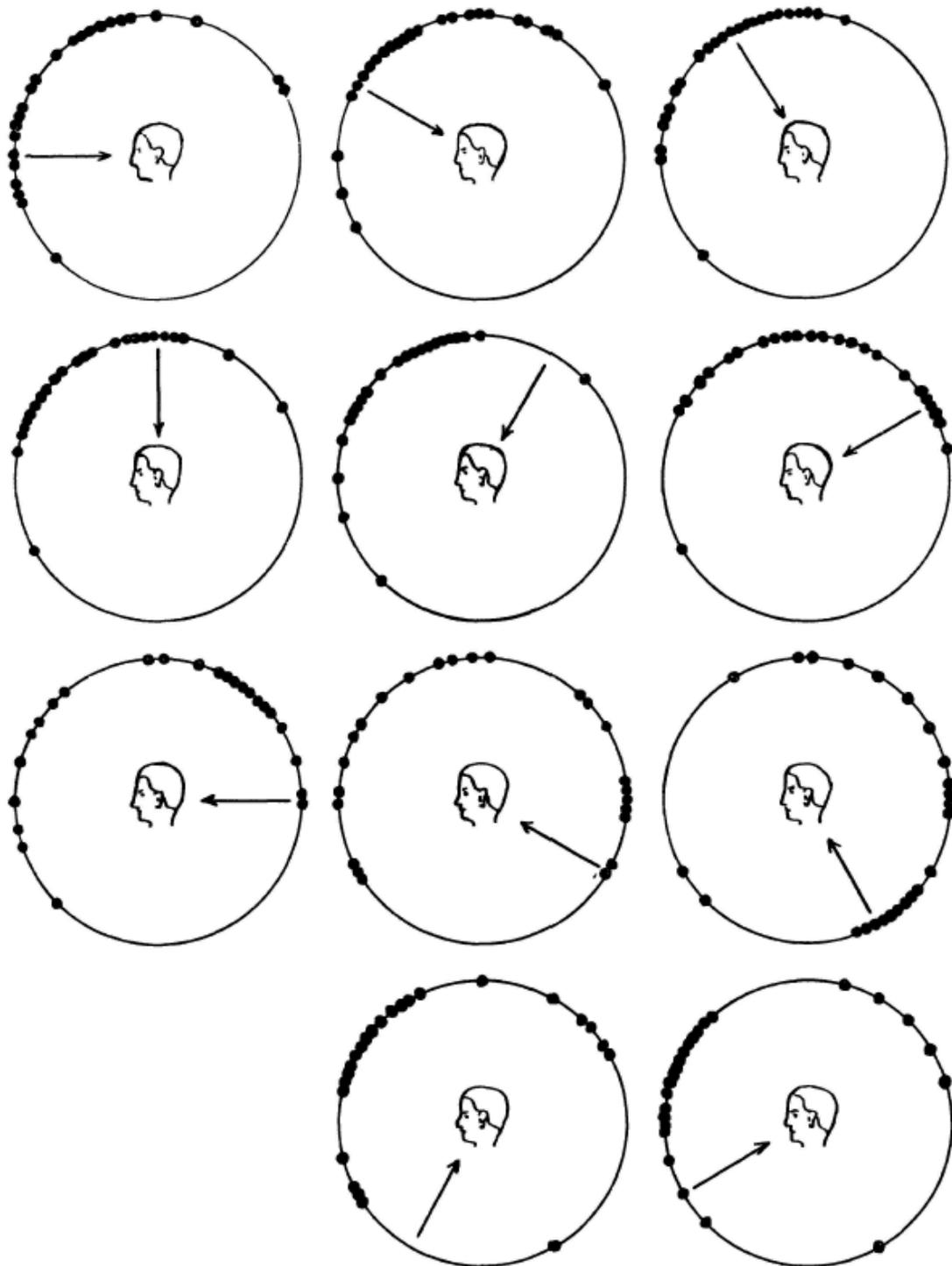


Figure 15: Localization of sound stimuli in different directions of the median plane presented to 24 test subjects.

moves his head, for example by 10 degrees to the right. By means of this width of this head movement, he obtains a perception by labyrinthine and proprioceptive sensations. Possible time differences yield information on the relative angular movement of the sound source. If

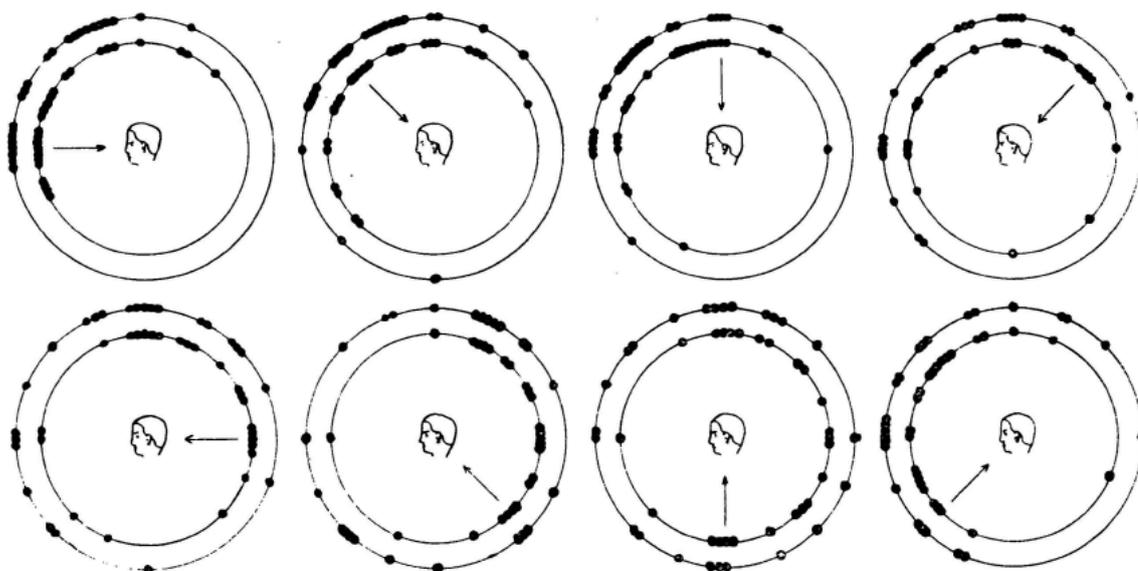


Figure 16: Localization in the time-difference-equivalent directions of 30° to the right (the outer circle) and to the left (inner circle) with 24 test subjects.

the person finds that the sound source has moved to the left by 10° , then he knows for sure that the source is in front in the horizontal plane. If the perceived shift is 10° to the right, then the sound source is located behind in the horizontal plane. If the subjective displacement of the sound source measured by the angle is less than the head rotation, the sound is localized either more upwards or downwards, depending on how small the ratio of these two factors is. Since the time difference, caused by the relocation of the sound source, is perceived through the cochlear nerves and the rotation of the head mainly through the vestibular nerves, we can call the relationship between the angles obtained from the former and the latter quantity the *cochleo-vestibular quotient of kinetic directional hearing*. The significance of this quotient is not limited to the head rotation in the horizontal plane, but also applies to all other movements of the head in the following way: *as the sound source is located closer to the plane of rotation, the quotient becomes larger, and the closer we are to the axis of rotation, the smaller the quotient becomes*. It does not matter on which side the direction of the sound source itself is. Through some small head movements, often carried out unconsciously, the direction of the sound is always clear. When hearing a strange sound, humans, as well as some animals instinctively turn their head to the side of the sound, primarily in an inherent way, to see the reason for the sound by their eyes, but probably also to localize the sound precisely by kinetic directional hearing, which is more easily performed if the sound is closer to the median plane, i.e., it moves further into the foveal range of directional hearing. Due to the low value of the threshold angle in the median plane range of the auditory space (1° - 1.5°), kinetic sound localization is very accurate, and this explains the fact that in daily life we experience little of the huge astigmatism which is characteristic to our static directional hearing.

Considerations on the propagation of directional hearing stimuli in the auditory pathways

Since there are no experimental investigations in this field up to now, I find it appropriate to study these conditions as far as the current state of research in physiology of hearing will allow. The anatomy of the auditory pathways has been treated briefly by [DAVIS \(1934\)](#). It is interesting to learn that the primary neurons of the auditory nerve end partly in the ventral part and partly in the dorsal cochlear nucleus (nucleus nervi cochlearis). From these arise the second level neurons that pass to the medial geniculate body (corpus geniculatum mediale) either directly or via intermediate neurons along the crossed lateral lemniscus (lemniscus lateralis). Whereas the majority of these neurons cross the center line, yet there exist also ipsilateral connections between the cochlear nucleus and the medial geniculate body. The latter one is connected to the cortex through auditory connectivity consisting of higher order neurons that are wired like a fan to the front edge of the upper temporal lobe, where they reach deep into the Sylvian fissure (sulcus lateralis cerebri). This region should be the central area for the entire auditory cortex, and only after passing through this zone the impulses can enter the surrounding cortex.

Since [WEVER and BRAY \(1930\)](#), with their classic work on the nature of the action potentials of the auditory nerve, indicated the way for further investigations, the study of these phenomena has taken on a solid basis. — The cochlear action potentials that are much stronger than those of the auditory nerve are probably not directly related to directional hearing. On the other hand, one can observe in the action potentials along the auditory pathway, phenomena that one would like to connect with sound localization.

According to studies by [DAVIS \(1934\)](#), pulses can be obtained from the auditory nerve up to 3000 Hz that are synchronous to the stimulus tone; these are however much weaker from 2000 to 3000 Hz than for lower frequency tones. If the tone frequency is above 1000 Hz, then in addition to synchronous pulses we can observe also asynchronous pulses, and the more so the higher the tone is; at frequencies above 3000 Hz all pulses are asynchronous. It appears from preliminary announcements by [DAVIS](#) that what was said also applies to the secondary neurons in the lateral lemniscus. In the inferior colliculus, which is passed through by some of the connections between the cochlear nucleus and medial geniculate body, most of the synchronization ceases already below 1000 Hz. In the medial geniculate body, with the exception of a pulse burst occurring during the onset of sound, synchronous pulses have not been detected anymore. The more synapses the pulses pass through, the lower the amount of synchronous pulses, and the more prominent the onset effect becomes. According to the author, this effect is undoubtedly due to the good synchronization of the first pulse burst and the subsequent asynchronous action. Regarding the electrical activity of the cortex, with click signals or at the onset of a tone, one can observe an electropositive spike after a latency of about 8σ , which has reached its maximum within 3σ , and decays even more slowly. The frequency of the stimulus tone is not reproduced anymore, and one cannot find any localization regarding the pitch of the sound at the cerebral cortex.

In two places in his publication [DAVIS](#) mentions directional hearing. In connection with the action currents of the inferior colliculus he expressed: - "which is probably a relay station for

reflex responses of orientation to sounds” - and in the theoretical considerations at the end of the publication: ”Another implication is that the reproduction in the pattern of the nerve impulses of the frequencies of incident sound waves is to be regarded as incidental to the mechanism of excitation of the auditory nerve fibers, and of little or no significance in determining the attributes of sensation. It is probably of considerable importance, however, in the binaural localization of the source of sound on the basis of phase or time differences”.

Regarding these comments, especially the former one, the author does not give any rationale. Certainly the experimental facts he identified are of great interest here, as we have found that click noises as well as quickly on and off switching sounds are easy to localize. On the other hand, these are the only sounds whose effect is not limited only up to the medial geniculate body, but extends to the cerebral cortex (the author speaks about the impulses at the offset of a sound only in connection with the action potentials of the cochlea). We can imagine that somewhere in the brain there are ”places” capable of receiving input from both sides of the auditory pathway. Then the earlier arriving impulses occupy a number of these ”places” so that the impulses from the contralateral ear, arriving later, cannot produce as much effect as the initial ones, and the ”balance of directional judgment” is bent towards the earlier ones. If the impulses from both sides enter these positions simultaneously, then balance is not disturbed, and we perceive a localization of sound in the middle. Since the velocity of propagation of excitation differs between different nerve fibers, the impulses from the contralateral side arrive within a very short time difference, after which only a few ”places” are occupied by the first-arriving impulses, and we perceive less side localization than when the time difference is large and the majority or all impulses of one side have reached their goal. If there is a small time difference together with an opposite large difference in intensity, the number of active elements in this ”place” is greater than in the former one, and the leaders of the ”race” are the impulses superior in number, which can win over the minority of pulses coming from the other side. This can explain the fact, observed by several authors, that small time differences can be compensated by opposite intensity differences. The double sound can be explained the following way: if the time difference is greater than the time difference created naturally, the refractory period after the impulses that arrive first will have passed already and the synapses can receive impulses from the opposite side, resulting in localization on the side associated to those endpoints.

These circumstances also suggest that the time difference represents a most important factor in directional hearing. The fact that some animals, despite their shorter ear distance, can localize better than humans (see p. 5), could be due to the shorter auditory pathways of these animals. Consequently, the distribution of pulses due to different conduction velocities in the auditory nerve fibers becomes narrower, whereby the frontage of the first arriving impulses becomes accordingly denser.

Final remarks

In our normal binaural hearing, a directional content is always associated which is perceived more clearly with impulsive and noise sounds but more blurred with other sounds. Just as we locate our visual, touch, heat, cold, pain, and proprioceptive sensations, we do so with our auditory sensations. If the binaural effect is artificially switched off, as with ordinary radio listening, an unnatural impression is obtained that is based partly on the absence of sound localization, partly on the lack of full tone color, the plasticity of sound. This difference in sound quality of monaural and binaural hearing has not been explained so far.

The major influence of time differences in directional hearing can be regarded as a proven fact. Already the small magnitude of the direction angle threshold (at best $< 1^\circ$) makes it difficult to consider a different fact instead of the time difference. With such small angles, however, the time difference is also surprisingly small, less than $1/100000$ of a second. Without sharp calibration lines we are not able to observe small distances in measurement devices, and similarly small time differences disappear when a sound does not contain any sharp timing marks. As we recall, those time stamps are found only in non-periodic acoustic phenomena (impulsive sounds, noise). Since these can be decomposed into frequency components, it is evident that just the high frequency components are of significance for these smallest of time differences. If the frequency of a component is 1000 Hz, the smallest observable effective path length makes up only 1% of the wavelength, and the sound pressure difference calculated from the effective phase at each frequency is not more than 3% of the limit value. The exploitation of such a frequency component of a sound is therefore much smaller than that of a component at 10000 Hz, where the smallest effective path length difference is 10% of the wavelength and the sound pressure difference between the ears is 62% of the overall sound pressure amplitude. Here we see that sound components, which are still far below the upper frequency limit of hearing, can well play their role as time markers in directional hearing. Here we come ultimately to the conclusion that phase differences are effective factors, but in another sense than those authors who propose the phase differences of prolonged tones to be significant in directional hearing. Here it is only a question of a randomly and sporadically starting and stopping sound component, which is so high in frequency that it seems questionable whether it, by periodic repetition, could cause any synchronous stimulation of the auditory nerve, and would be perceived subjectively as an ultra-musical hissing sound. When such a sound component arrives the hair cells in the cochlea emit a swarm of impulses, of which those originated from the ipsilateral ear reach the target earlier than the ones from the contralateral ear, which would result in side localization of the sound. If these components are periodically repeated, the following sound waves are not likely to cause any similar impulse burst, since the hair cells are still in the refractory stage. So far as this stage fades away, the hair cells could respond to new waves again, but this should happen irregularly, and would not take place simultaneously in both ears. This circumstance, which among others explains that only the first burst and a subsequent weak aperiodic pulse discharge is obtained in the action potential oscillography of the auditory nerve, explains in my opinion the low directional thresholds for aperiodic and the high thresholds for periodic sounds. At low frequency tones (below 500 Hz) that are able to emit an equal burst of impulses for each period, since in this case the refractory period is shorter than the period, localization could therefore be

possible due to phase differences. Yet the sound pressure fluctuations in these tones occur so slowly that the important front of the impulses will be blurred. For three other reasons, I cannot conceive any greater importance for phase differences in the directional perception of sound:

1. because the investigations of those authors who have carried out their experiments with electrical tuning forks are not quite perfect,
2. because the percentage of those low frequency tones, where the phase differences may play a role, was relatively low in all sounds listened to by us, especially since they never occur in nature in a pure form.
3. because my own studies did not provide sufficient justification for the phase theory.

The designation of "intensity difference" is suitably replaced by "sound color difference" since the intensity of noise as well as that of complex tonal sounds is not clearly defined. The theoretical possibility that, when the ear position is changed, the conditions of sound components remain unchanged although the overall intensity is changed, should never occur in nature. Such an intensity difference can be produced only by applying a resistive potentiometer and headphones. The experiments carried out in this manner yielded however a result, according to which such intensity differences have no significant influence on localization. The naturally occurring sound color differences can be imitated by the artificial head, but it is impossible to eliminate the resulting time differences. Since these two differences also occur always together in nature, it might seem questionable, for which one of them we should give preference to: the time difference or the sound color difference. From my experiments with binaural sound transmission (see pages 39 and 40) it is proven that similarly small thresholds can be obtained by time difference alone (with microphones only) than when we consider sound color differences (by using the artificial head). Nevertheless, sound color differences are likely to play a role in binaural hearing. To some extent they can help to decide between different time-difference-equivalent directions, provided that the sound color is known in advance. The sound color of a source located behind our head is darker than when the sound source is brought to the front. If we bring one of two sound sources with identical sound color to the front and we leave the other one behind, then the test subject (these experiments have been carried out on many subjects) usually easily distinguishes one from the other. If the sound color of the first source is made "darker" (emphasis on low frequencies) and the latter one is made "lighter" (emphasis on high frequencies), the test subjects confuse the two sound sources almost without exception, as they judge the front and back location according to the sound color. Such a mistake in static sound localization is immediately detected when the subject makes small head movements, i.e., applies kinetic localization.

We have previously spoken about the time-difference-equivalent cones. In a closer mathematical examination it proves to be a two-shell hyperboloid rather than a cone. The deviation from a cone is however significant only if the sound source is located near the head of the test subject. For distances larger than 50 cm the curvature plays no practical role anymore, and we can simplify things so that instead of the hyperboloid, its asymptotic cone is regarded as a time-difference-equivalent. If we consider only, e.g., the horizontal plane instead of the entire auditory space, then our calculations of the hyperbola and its asymptotes can be based on those of [VON HORNBOSTEL \(1922\)](#).

The "astigmatism" of directional hearing is not an error in the same sense than that of the eyes. It is an inevitable consequence of the perception of direction with only two acoustic

points. If we had three such points, the time-difference-equivalent cone would disappear, and each sound direction would be time-difference-equivalent to its mirror image on the other side of the plane determined by these three points. Only with four ears that are not in the same plane could we identify the sound direction uniquely by time differences. The kinetic sound localization compensates, however, for this imperfection in our spatial hearing, and therefore the function of the labyrinth should be of great importance in sound localization, as in all of our orientation in the space surrounding us.

Summary

As is evident from the historical overview, there is no consensus on the specific stimulus factors in directional hearing, but the intensity, phase, and time differences are addressed as such ones. More recent studies, particularly those by VON HORNBOSTEL, provide support for the view that time differences are most relevant to directional hearing.

My own studies relate to 1) the external factors effective in directional hearing (intensity, phase and time differences), and 2) the directional hearing resolution itself.

The intensity differences at the two ears were examined by determining the thresholds of hearing at different angles of incidence of the stimulus tone. With low frequency tones the intensity differences are small; at higher frequencies they become larger as frequency increases. The sound intensities in different directions in the same plane do not follow the same law at all frequencies, but even with one and the same test subject they show irregularities, which are probably based on reflection, diffraction, and resonance phenomena due to anatomical relationships. For this reason, the frequency spectra (= sound colors, timbres) of composite sound phenomena (complex tonal sounds, noises) are unequal in different directions. (Thus the term "sound color theory" would then be more appropriately called 'intensity theory'). The same factors were also found in the experiments carried out using the artificial head, which enabled oscillographic analysis of the sound effects by using its ear microphones. Also, with the artificial head the phases (= time differences) were examined at different frequencies. The results confirmed the validity of the VON HORNBOSTEL–WERTHEIMER theory which states that the constant $k = 21$ cm represents the effective path length between the ears in the lateral direction of the sound.

The determination of directional hearing resolution was executed in a manner analogous to the examination of visual resolution, i.e., by determining the smallest angle at which one can distinguish two successively presented acoustic point sources. It would be inappropriate to use the deviation from the median plane as a reference point for determining the directional threshold angle, since the subjective median plane is unstable as shown by the experiments. The experiments using impulsive sounds had proved that two points are distinguishable if their effective time differences exceed a certain minimum value that is constant for all side directions of the sound sources. As a result, the directional hearing threshold angle β (in the median plane = α_0) increases along with an enlargement of the base side angle α according to the formula $\beta = \alpha_0 \sec(\alpha)$. This is true not only in the horizontal and frontal planes but also in all other planes that are perpendicular to the median plane. With unilateral ear closure the threshold angles are greater than if the two ears are open. Similarly, the thresholds increase if the color of the click signals is made darker. For tones, the threshold angles become smaller as the onset and offset times become shorter. In the case of tone mixtures and continuous noise the threshold angles are small since these sounds are only seemingly continuous. For continuous tones, which do not contain "time markers" for determination of direction, the angle thresholds are large. This observation speaks against the importance of phase and intensity differences in directional hearing. By continuously varying the phase difference, no clear rotating sounds could be produced.

In addition to localization, the *binaural-electrical sound transmission* also revealed the fullness of sound that is lacking in usual transmission (radio, cinema sound, etc.). Here the sound source was located toward the side direction at a microphone distance of 22 cm ($k = 21$ cm!). If the microphone spacing was increased to more than $2k$, a double sound appeared. The intensity differences did not provide any out-of-head localization of sound. But if the intensity difference was increased to 5- to 10-fold, then the sound was duplicated in such a way that one part is observed in the direction corresponding to the time difference and the other part in the more strongly stimulated ear.

Sound localization will take place in any of the *time-difference-equivalent directions*, which together form a *cone* (actually a hyperboloid). Between these directions, a spontaneous change of direction occurs as a result of "psychological" factors. The investigations carried out with the head in a free sound field showed that our directional hearing is so far "astigmatic" as we often fail to distinguish the time-difference-equivalent directions from each other. This affects only "static" localization, i.e., directional hearing in the case where the head of the observer remains immobile. In "kinetic" directional hearing, that is, in the case where the observer moves his head, he obtains sensations of time difference changes through the cochlear path and sensations about head position movements through the labyrinth path, whereby the *cochleo-vestibular quotient* yields the subjective localization of the sound.

Finally, the most recent studies on the excitation processes in the auditory pathways are discussed and the time difference as a specific directional hearing cue is explained in the light of those studies.

Literature references

- AGGAZZOTTI, A., Arch. di fisiol. 1921. 19.33. Ref. Ber. ü. d. ges. Physiol, 9. 280.
 —"— Boll. Soc. ital. Biol. sper. 1929. 4 564. Ref. Ber. 52. 309.
- ALLERS, R. u. BÉNESI, O., Z. ges. Neurol. u. Psychiatr. 1922. 76. 18.
- ALLERS, R., Psyche 1922. 3. 161. Ref. Ber. 19. 537.
 —"— Monatschr. Ohrenheilk. u. Lar.-hinol. 1924. 58. 422.
 —"— u. SCHMIEDEK, O., Psychol. Forsch. 1924. 6. 92.
- BANISTER, H., Brit. journ. psychol. a. gen. sect. 1924. 15. 80. Ref. Ber. 28. 294.
 —"— Brit. journ. psychol. 1925. 15. 280. Ref. Ber. 31. 113.
 —"— Brit. journ. psychol. 1926. 16. 265. Ref. Ber. 37. 178.
- BARD, L., Journ. de physiol. et de pathol. gén. 1921. 19. 216.
- BÉKÉSY, G. v., Physik. Z. 1930. 31. 824 u. 857.
- BONACINI, C., Arch. di fisiol 1933. 32.490. Ref. Ber. 77. 154.
- BOWLKER T. J., Philos. Magazine. 15. 318. Ref. Jahresb. Physiol. 1908.
- BRUNZLOW, Z. Sinnesphysiol. 1925. 56. 326.
- DAVIS, H., A Handbook of General Experimental Psychology. Worcester, Mass. 1934. 962.
 —"—; DERBYSHIRE, A. J.; LURIE, M. H. u. SAUL, L. J., Amer. Journ. Physiol. 1934.
 107. 311.
- DOEVENSPECK, H., Z. Sinnesphysiol. 1927. 58. 308.
- ENGELMANN, W., Z. Psychol. 1928. 105. 317.
- ESSEN, Ja. van, Nederl. Tijdschr. Psychol. 1934. 2. 386. Ref. Ber. 87. 397.
- FRY, Thornton C., Physik. Ztschr. 1922. 14. 273.
- GATSCHER, S., Wien. klin. Wschr. 1924. 37. 731.
- GILSE, v. u. ROELOFS, O., Acta oto-laryng. 1930. 14. 1 u 79.
- GOLDSTEIN, K. u. ROSENTHAL-VEIT, O., Psychol. Forsch. 1926. 8. 318.
- GRÜTZMACHER, M. u. MEYER, E., Elektr. Nachr.-Technik 1927. 4. 203. Zit. Trendelenburg
 1930. 827.
- GUNS, P. u. ROUSSE, C., Ann, Mal. Oreille 1929. 48. 813. Ref. Ber. 53. 258.
- HALVERSON, H. M., Psychol. Monogr. 1922. 31. 7. Ref. Ber. 15. 117.
 —"— Am. Journ. Psychol. 1922. 33. 178.
 —"— Am. Journ. Psychol. 1927. 38. 97.
- HARTLEY, R. V. L. u. FRY, Thornton G., Phys. Rev. 1921. 4 .532. Ref. Ber. 9. 280.
- HARTRIDGE, H., Journ. of physiol. 1934. 81. 17 P.
- HECHT, H., Naturwissenschaften 1922. 10. 107.
- HELMHOLTZ, Die Lehre von den Tonempfindungen. Braunschweig 1913.
- HOLT-HANSCH, Z. Psychol. 1931. 120. 209.
- HORNBOSTEL, E. M. V. u. WERTHEIMER, M., Sitzungsber. d. preuss. Akad. d. Wiss. Berlin.
 1920. 388. Ref. Ber. 2. 332.
- HORNBOSTEL, E. M. v., Jahresb. ü. d. ges. Physiol. 1922. 1. Hälfte. 389.
 —"— Psychol. Forsch. 1923. 4. 64.
 —"— Handb. d. norm. u. path. Physiol. 1926. X I. 602.
- HUMBY, S. R., Nature (London) 1930. II. 682.

- JEWETT, F. B., *Science* (N. Y.). 1933. I. 435. Ref. Ber. 74 . 331.
- KIEFER, MARIA, *Arch. f. d. ges. Psychol.* 1922. 42. 185.
- KLEMM, O., *Arch. f.d. ges. Psychol.* 1920. 40. 117.
- KREIDL, A. u. GATSCHER, S., *Zbl. Physiol.* 1920. 34. 490.
- ”— *Pflüg. Arch.* 1923. 200. 366.
- ”— *Pflüg. Arch.* 1925. 207. 85.
- LACHMUND, H., *Z. Psychol.* 1921. 88. 1 u. 53.
- Lo SURDO, A., *Atti d. R. accad. naz. dei Lincei. Rendiconti.* 1921. 30. 125.
Ref. Ber. 9. 280.
- LÜBCKE, E., *Z. techn. Physik* 1934. 15. 652. *Zit. Trendelenburg* 1935. 145.
- MARX, W. u. MARX, H., *Beitr. z. Anat. Physiol Pathol. u. Therap. d. Ohr. d. Nase u. d. Hals.* 1921. 16. 32. Ref. Ber. 7. 83.
- MEYER, E. u. BUCHMANN, G., *Biol. Ber. Physik.-math. Kl.* 1931. 32. 735. *Zit. Trendelenburg* 1935. 115.
- MONJE, M., *Z. Sinnesphysiol.* 1935. 66. 7.
- MORE, L. T. u. FRY, H. S., *Philos. Magazine* 13. 452. Ref. *Jahresb. f. Physiol.* 1907.
- PEREKALIN, W. E., *Z. Hals- usw. Heilk.* 1930. 25. 442.
- RAUCH, M., *M Schr. f. Ohrenh. u. Lar.-Rhinol.* 1922. 56. 176 u. 183.
- Lord RAYLEIGH, *Philos. Magaz.* 13. 214 u. 316. Ref. *Jahresb. Physiol.* 1907.
- REGEN, J., *Sitzungsb. d. Akad. Wien, Math.-naturw.* 1924. 132. 81.
- RETJÖ, A., *M Schr. Ohrenheilk.* 1931. 65. 959. Ref. Ber. 63. 790.
- RENQVIST-REENPÄÄ, Y., *Allgemeine Sinnesphysiologie.* Wien, 1936.
- SCHEMINZKY, F., *Die Welt des Schalles.* Graz, Wien, Leipzig u. Berlin 1935.
- SEASHORE, C. E., *Psychol. Monogr.* 1922. 31. 1. Ref. Ber. 15. 116.
- SHAXBY, J. H. u. GAGE, F. H., *Med. res. council* 1936, spec. rep. 166. 1.
- STEVENS, S. S. u. NEWMAN, E. B., *Proc. Nat. Acad. Sci. USA.* 1934. 20. 593.
- STEWART, G. W., *Physic, Review* 1920. 15. 432. (I)
- ”— *Proc. Nat. Acad.* 1920. 6. 166. (II)
- ”— *Psychol. Monogr.* 1922. 31. 30. Ref. Ber. 15. 117.
- TRENDELENBURG, F., *Abderhald. Handb. V. 7.* 1930. 787.
- ”— *Klänge und Geräusche.* Berlin 1935.
- TRIMBLE, O. C., *Am. J. Psychol.* 1929. 41. 564.
- TRÖGER, J., *Physik. Z.* 1930. 31. 26.
- TULLIO, P., *Arch. ital. de biol.* 1926. 77. 58. Ref. Ber. 41. 798.
- VALENTINE, W. L., *Journ. of comp. psychol.* 1927. 7. 357.
- WIEN, M. v., *Pflüg. Archiv.* 1903. 97. 1.
- WILSKA, A., *Skand. Arch. f. Physiol.* 1935. 72. 161.
- YOUNG, P. TH., *J. of exper. Psychol.* 1928. 11. 399. Ref. Ber. 49. 675.

Appendix: Additional photos of the artificial head

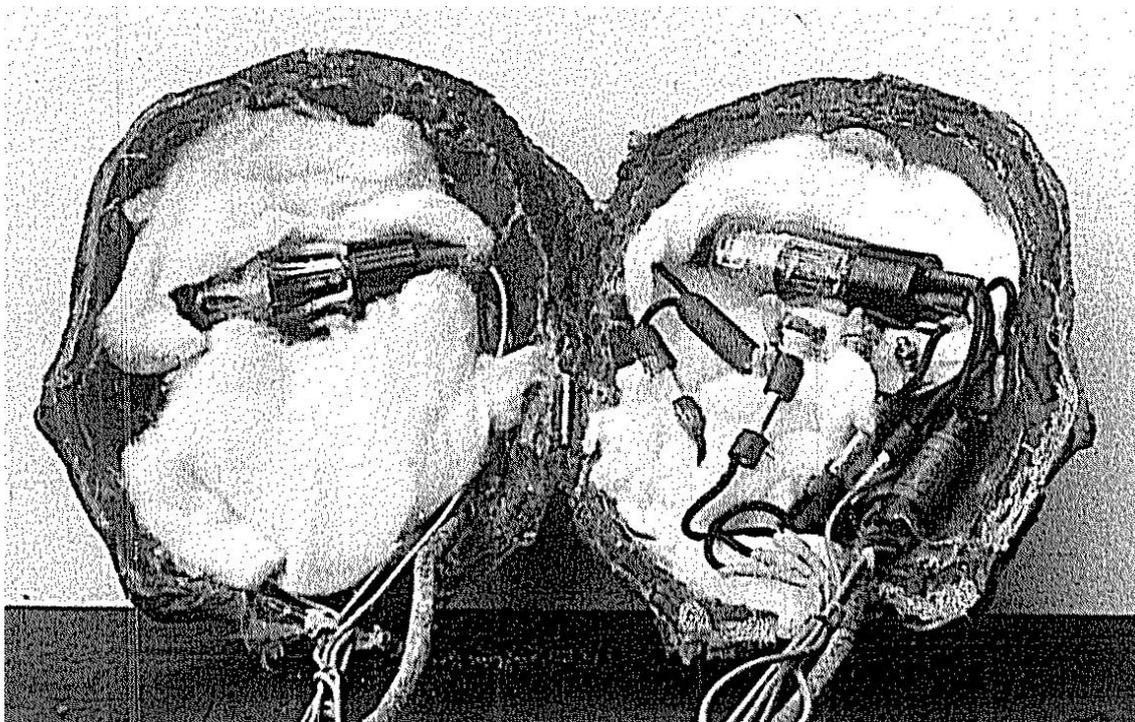


Figure 17: Artificial head halves open (same as Fig. 4c).

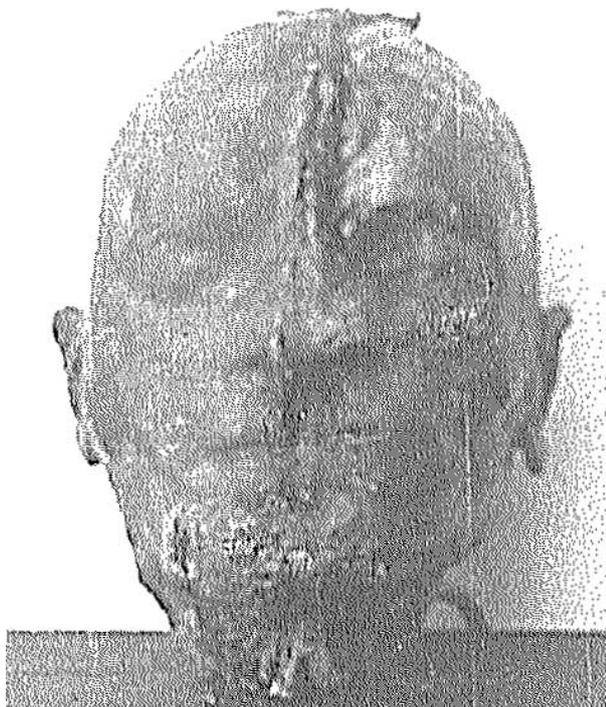


Figure 18: Artificial head halves closed.