The Journal of Laryngology and Otology
January 1981. Vol. **95**. pp. 29–40

Sound localization

Part I: A brief history

By F. S. HICKSON and V. E. NEWTON (Manchester)

Introduction

SPACE perception is commonly conceived in a visual context. The accuracy of the eye has overshadowed the importance of the ear yet it is the ear which is in constant vigil in monitoring our environment.

Sound has long been known to evoke the subjective sensations of pitch and loudness but not until recently has the accuracy of the ear been recognized to be of such an extent as to utilize the differences in physical conditions at the two ears in sound localization. Not only were the physical parameters in need of identification by the scientists, but a physiological process by which such parameters could be accurately perceived was to be accepted before sound localization was recognized as a real phenomenon.

Prior to the mid-nineteenth century, interest in sound localization was largely confined to the empiricist philosophers' attitude whereby sound was believed not to possess spatial attributes. Such an attitude was held by Berkeley and James Mill, for instance, who believed that localization of sound was achieved merely by the use of prior experience and by visual and tactile cues.

The Intensity Theory

When a sound source lies outside the median plane there is a difference in intensity of the sound arriving at the ears of the listener due to the different distances involved and the sound shadow cast by the head.

In the late-eighteenth century, Venturi (1796) had demonstrated the ability of subjects to localize the notes of a flute at various positions in a field. He suggested that intensity differences at the two ears were the cue to localizing sound but his work received little attention.

The intensity theory was not again experimentally verified until the work of Rayleigh (1877). He explained that the difference in intensity at the two ears provided a cue to localization but that ambiguities arise because there are two possible directions of the source for each interaural intensity difference. Also sounds from the median plane give equal intensity at each ear, leading to front-back confusion (see Fig. 1).

Firestone (1930) measured intensity differences and found that, for frequencies near or below 1 KHz, the values of interaural intensity differences for an artificial head were negligible in the median plane and

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

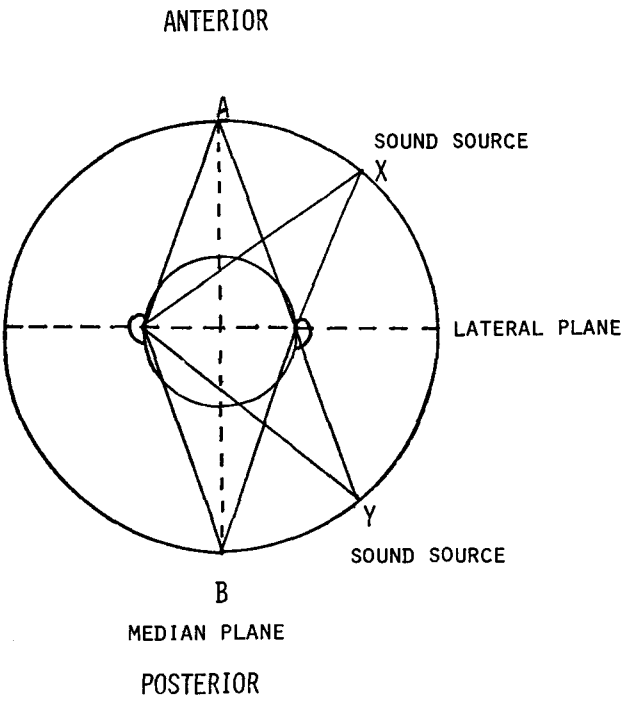


FIG. 1

Diagram illustrating front-back confusion in the horizontal plane.
Sound sources A and B. The path distance to the left and right ears is the same for these sound sources situated in the median plane.
Sound sources X and Y. The path difference from each of these sound sources to the left and right ears is the same.

increased as the source approached the sides, in line with the two ears. For low frequency sounds below 1 KHz, the head shadow is negligible since the wavelength is large and the waves are diffracted round the head. For a tone of 2 KHz, however, the intensity differences are of an irregular function. This is due to minima created by complex phase relationships of waves arriving from the front and from the back of the head. Nordlund (1962a) confirmed these findings and concluded that at high frequencies the only reliable method of localization would be to equalize the intensity in each ear by moving the head so that the source was in the median plane. Intensity cues are thus seen to be of most value in the localization of mid-frequency sounds of about 1 KHz to 2 KHz.

The Time Theory

The theory of sound localization by interaural time differences was first proposed by Malloch (1908).

Klemm (1920) found in dichotic experiments that a slight interaural

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

delay resulted in the lateralization of a tone towards the ear receiving prior stimulation.

Nordlund (1962a) was able to measure time differences across the head from a single source. However, as with intensity cues, ambiguities arise resulting in front-back confusion but can be resolved by turning the head so that the ear approaching the source receives progressively shorter time delays as the head is turned. For low frequency sounds Nordlund found significant time delays across the head but for high frequencies further ambiguities arose from the complexity of phase relationships of the sounds arriving at the two ears.

Interaural Phase Differences

The role of interaural phase differences in sound localization was first proposed by Thompson in 1878. Thompson used two tuning forks, one of frequency 128 Hz and the other with a slightly different frequency. He led the sound from the forks one to each ear, and by rotating one fork was able to produce a subjective sensation of movement of the acoustic image. Similar experiments confirmed the perception of phase (Rayleigh, 1907; More and Fry, 1907; Wilson and Myers, 1908).

Experimenting with the use of an artificial head, Nordlund (1962a) concluded that it should be possible to localize pure tones below 1,400 Hz by means of phase differences in the angular range $\pm 90^{\circ}$ from the median plane. For tones above this frequency, however, the wavelength is less than the distance between the two ears of the subject and mislocalization can arise where the far ear receives waves leading in phase with respect to those at the near ear (Casseday and Neff, 1973). Again ambiguities can be overcome by head movements.

Other factors in localization

The explanations concerning interaural time, intensity and phase did not account for all aspects of the phenomenon of sound localization. They provided no explanation for the resolution of front-back confusion, nor could localization in the median plane be possible without additional cues.

The pinna

In 1893 Bloch proposed that the pinna was involved in removing front-back confusion by intercepting sound waves from the rear and by reflecting those arising in front.

Mach (1906) developed the idea of the pinna's role by producing an analysis which emphasized the need for such a three-dimensional structure to perceive direction.

Batteau (1967, 1968) proposed that the pinna creates a series of delay paths dependent on the orientation of the sound source with respect to the pinna.

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

A comb filter mechanism was suggested by Blauert (1970) as an explanation of the role of the pinna. It was thought that by selective filtering of the sound signal there would be a relative boost given to those parts of the signal which lie in certain frequency bands which depended upon the direction of the incident sound.

Fisher and Freedman (1967) suggested that pinna cues are only of use when head movements are restricted and that usually these cues are redundant.

Angell and Fite in 1901 found the pinna to be of utmost importance in monaural localization and that in subjects who were completely deaf unilaterally errors were slightly greater than in those with binaural hearing but that distinctions between front and back were superior in the case of monaural subjects. Ten monaural cases were studied by Jongkees and van der Veer (1958) who found only two to have normal directional hearing.

Head movements

Wallach (1940) showed that head movements could aid localization in both the horizontal and vertical planes. Nordlund (1962a) asserted that the head must be movable for accurate localization either of high frequencies or in the median plane.

Visual information

Lackner (1973) found that visual information prevented errors between actual and registered head position and so prevented errors in auditory localization for various head postures.

Shoulder reflection

Gardner (1973) describes reflection of low frequency sound waves in assisting localization of noise stimuli.

Tactile sensations

Early theories propounded that tactile sensations of the medium transmitting sound were of importance in localization. In 1893 Wundt believed localization to arise from tactile sensations received by the pinna, drum and tensors of the drum.

The semi-circular canals

In 1881 Laborde suggested the possibility of the function of the semi-circular canals in detecting acoustic direction. Others supported this theory and suggested the role of head movements in stimulating the canals (Preyer and Arnheim, 1887; Munsterberger, 1889). Von Kries (1890), however, had cast doubt on the theory of the role of movement in localization by the canals since two differing sounds of separate locations can each be localized simultaneously. There remained support for the

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

canal hypothesis as late as 1954, when Meurman and Meurman postulated that fenestration of the lateral semi-circular canal damaged the middle ear acoustics in transmitting the sounds to the canals and consequently fenestrated patients were poor localizers.

More recent refutation of vestibular involvement has been provided by Jongkees and van der Veer (1958). They found that patients with no vestibular function in the ears had normal directional hearing abilities. They had also found previously (1957) that otosclerotic patients had poor localization ability both before and after fenestration. Nordlund (1964) has also shown that patients with vestibular dysfunction can localize sounds normally.

Such explanations of tactile and vestibular involvement were difficult to refute in the light of the existing knowledge of the physical conditions at the ears. As the intensity, time and phase theories were established, acceptability of these early hypotheses weakened. Animal experiments then focused on the neurophysiological mechanisms of the auditory pathways in the transmission of the interaural differences to the higher centres of the nervous system.

Animal experiments

Moushegian and Rupert (1974) found the responses of some neurons in the medulla to be sensitive to interaural time and intensity, and some to phase differences.

Galambos *et al.* (1959) and Hall (1965) demonstrated sensitivity to time, Harrison (1974) to intensity, and Goldberg and Brown (1969) to intensity and phase information at the level of the superior olive.

Aitken *et al.* (1970) observed sensitivity to interaural phase cues in the lateral lemniscus network.

Brugge *et al.* (1969) have found single units within the auditory cortex which code information from interaural time and intensity differences.

Animal behaviour experiments have appeared to indicate that binaural interaction for encoding of the information necessary for localization takes place in the superior olivary complex (Masterton *et al.*, 1967; Casseday and Neff, 1975). Comparative animal studies support this hypothesis (Harrison and Feldman, 1970; Harrison, 1974) though both physiological and behavioural experiments would seem to indicate a role for higher centres in directional hearing (Evans and Whitfield, 1964; Strominger and Oesterreich, 1970; Heffner, 1978).

Clinical Tests

Since the auditory pathways are involved in the perception of time, phase and intensity it would seem appropriate to postulate that lesions of these pathways may be manifested in poor sound localization.

Several attempts have been made clinically to associate poor source discrimination with lesions of specific parts of the auditory pathways.

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

Such attempts have involved complex clinical procedures of intracranial lateralization and free-field localization.

I. Lateralization investigations

These investigations involve sources of sound very close to each ear using headphones, an adapted stethoscope or speakers close to the head, whereby the sound in each ear can be adjusted independently with respect to time, intensity and phase until a right side, left side or median plane sensation is perceived within the subject's head.

Greene (1929)

Greene asked patients to identify the midline sensation when he stroked the tubing at various points of a stethoscope. This stimulus involved simultaneous time and intensity cues. He found the results of this test were abnormal in only one of forty-eight cases of temporal lobe lesions. In fifteen of these cases he found the shortest distance of tubing from the point which gave midline perception to the point which gave a sensation of lateralization. In five of these fifteen cases this was an abnormally large distance.

Greene also used an elaborate modified stethoscope to test the effects of time and intensity cues independently. In these tests he found that the minimum time cue, rather than intensity cue, was more useful in identifying temporal lobe abnormalities. A group with otological disease, including one case of acoustic neuroma, gave normal results.

Matzker (1959)

Matzker used a similar modified stethoscope and tested a group of patients with central abnormalities. He excluded those with unilateral hearing impairments. Matzker found that lateralization time cues for pure tones were abnormally large in patients with brain-stem and cerebral lesions.

Groen (1969)

Groen used a stethoscope with tubing which he tapped to give a stimulus. He thought that the intensity attenuation was negligible for different positions of tapping and that the time cue was the important parameter. Groen found that large interaural time cues were needed for patients with temporal lobe lesions but that acoustic neuroma patients could not lateralize at all. On the other hand, patients with cochlear hearing impairments gave normal results.

Walsh (1957)

Walsh investigated lateralization by two methods. First, using headphones, he found that all 21 of his patients with unilateral cortical

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

lesions could use time delays to lateralize to some degree. Secondly, using two speakers equidistant on either side of the head, all patients made use of time cues to give right and left judgements of clicks delivered with differences of small time intervals to the two speakers. Correct judgement was indicated by lateralization to the speaker having the preceding click. Walsh thus concluded that unilateral cortical lesions, and even total hemispherectomy, did not prevent patients from being able to lateralize sounds.

Jerger (1960)

Jerger combined a lateralization test with one of loudness balance. He asked patients to balance the intensity of tones in each ear and identified the time delay needed to achieve mid-line stimulation at these intensities. Jerger found this delay to be normal in most cases of cortical lesions. In cases with abnormal test results he suggested that sub-cortical pathways were involved.

Bosatra and Russolo (1976)

Bosatra and Russolo tested lateralization ability using time delays and intensity differences delivered dichotically to normal, healthy subjects, before and after administration of barbiturates, and to pathological subjects. The ability was found to be abnormal in patients with brain-stem impairment, both spontaneous and pharmacologically induced, and in a case of acoustic neuroma. Perception of time delay was found to be more frequently abnormal than that of intensity difference.

Nilsson and Lidén (1976)

The minimum interaural time delay detectable by patients with retrocochlear lesions was found to be abnormal in 12 out of 13 cases, using a 500 Hz pure tone stimulus presented with variable phase lag between right and left headphones.

II. Free-field localization

In contrast to the intracranial tests, the free field approach uses a single source, the intensity and time differences being mutually changed according to the position of the source relative to the subject. This method has the advantage of using a function of the subjects' auditory systems with which they are familiar. It does, however, involve the use of an anechoic room in which the norms of localization have been found.

Sanchez-Longo et al. *(1957; 1958)*

Sanchez-Longo eliminated visual and head movement cues by blind-folding and clamping the heads of subjects. Low frequency noise with a fundamental frequency of 60 Hz was used as a signal from a speaker

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

movable in the horizontal plane. Subjects were asked to indicate their estimate of the speaker's location with a pointer. Sanchez-Longo found that average errors on the right and left auditory fields were small for normal subjects but cases with temporal lobe lesions in most instances manifested impairment of sound localization in the contralateral auditory field to the side of the lesion.

Walsh (1957)

Walsh also carried out tests using free-field stimulation in the vertical and horizontal planes, with a musical box as the source. In various brain-stem and cerebral lesions he found the ability to localize in the vertical plane to be lost whilst localization in a horizontal plane remained possible.

Jongkees and van der Veer (1957)

Jongkees and van der Veer performed free-field tests in the horizontal plane on the localization ability of a wide spectrum of subjects with hearing disorders of both conductive and sensori-neural types and of varying unilateral and bilateral degrees. They found no correlation between directional hearing capacity and degree of hearing loss. They concluded that even small hearing losses may impair the ability to localize the direction of sound but, on the other hand, even total unilateral deafness may leave the directional hearing intact. Neither a conductive nor a perceptive loss necessarily resulted in impaired directional hearing. They did find, however, that otosclerotic patients had poor directional hearing, whether fenestration had been performed or not. They suggested that a good appreciation of the phase difference of a sound is impossible when the entrance to the labyrinth is blocked and that the fenestra novovalis further disturbs this phase change.

Jerger, Weikers, Sharbrough and Jerger (1969)

Free-field localization of various stimuli in the horizontal plane with the subject's head fixed was tested. A patient with bilateral lesions of the temporal lobe was found to have a consistently large average error for all stimulus types.

Nordlund (1962b, 1964)

Nordlund developed a technique to produce a test of localization in the horizontal plane in which he investigated normal and pathological subjects. In developing the test he found localization ability to be independent of the intensity of the stimulus if this was loud enough to be heard in the worse ear. Thence the loudness of the stimulus was adjusted to a comfortable level of binaural stimulation for the test. Nordlund analysed the results of each pathological group with respect to mean errors and their standard deviations and compared these with the normal range of errors.

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

Many of the 37 subjects with middle-ear lesions were found to have relatively poor directional hearing.

Of the 22 subjects with cochlear losses most had good directional hearing. Only two subjects had abnormal standard deviations of errors. Some others had abnormal mean errors but normal standard deviations.

Of the 8 subjects with lesions of the eighth nerve or pons all had abnormal standard deviations and most had abnormal mean errors.

Nordlund also tested 9 subjects with brain lesions and found their results to be generally normal.

Having examined his data, Nordlund suggested that a directional hearing test is of potential value in the diagnosis of lesions of the auditory nerve and pons.

Nordlund laid special emphasis on the abnormality of standard deviation of errors as opposed to mean errors, as a diagnostic sign in evaluating directional hearing. It is thus the inconsistency of errors, rather than any bias of error towards either direction, which he considered to constitute abnormal directional hearing.

Nordlund's results present a rigorous account of the potential of a directional hearing test. The procedure has been repeated by other workers.

Lidén and Korsan-Bengsten (1973)

These workers showed that a 500 Hz tone and low pass filtered noise were most effective in revealing sound localization impairment. They found abnormal directional hearing in 18 of 21 cases with acoustic neuromas, even though 13 of the cases had normal or near-normal pure tone audiograms. In agreement with Nordlund they found a mild to medium sensori-neural loss no obstacle to the test.

Nilsson, Lidén, Rosen and Zoller (1973)

Using a 500 Hz pure tone signal, the localization ability of 100 normally hearing subjects was tested using Nordlund's technique. No significant difference was found between male and female ability for this signal.

Nilsson *et al.* (1973) also compared this method with two other techniques and concluded that free-field testing was superior to methods involving stethoscope and headphone presentation.

The stethoscope method was dismissed as a crude technique useful only for imprecise investigation of directional hearing.

Free-field techniques involve the perception of a real source, a familiar task of everyday life in which the subjects had confidence in ascribing a specific location. Nilsson *et al.*, reported the difficulty of some patients, especially older subjects, in using phase cues in headphone presentation to establish a mid-line point. On the other hand, dichotic presentation does

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

allow the compensation of interaural differences of hearing threshold by loudness balancing prior to testing of lateralization ability by phase cues.

Terhune (1974)

Terhune used a free-field method in which subjects were asked to point to their estimate of the source. Terhune investigated several parameters with respect to localization and found no correlation of ability to localize with height, age, interaural distance or order of presentation of certain signal types.

Tonning (1975)

Tonning concluded that patients with impaired hearing can be expected to have worse directional hearing for white noise in the horizontal plane than those with normal hearing. It was also suggested that those with asymmetrical hearing losses can be expected to give poorer directional hearing test results than those with symmetrical losses. However, although these abnormalities are to be expected, some cases of poor hearing, both symmetrical and asymmetrical, did not affect localization ability.

Conclusion

The above studies show considerable interest in free-field techniques in the investigation of directional hearing. Nordlund's examination of the differences in directional hearing ability in various pathological types of hearing impairment is of particular interest with regard to a potential diagnostic test. Lidén and Korsan-Bengsten (1973) have vindicated Nordlund's work and this text presents an area for further investigation.

Acknowledgements

The authors wish to thank Professor I. G. Taylor and the Department of Audiology and Education of the Deaf, University of Manchester, for their help in the preparation of this paper.

REFERENCES

AITKIN, L-M., ANDERSON, D. J., and BRUGGE, J. F. (1970) Tonotopic organization and discharge characteristics of neurons in nuclei of the lateral lemniscus of the cat. *Journal of Neurophysiology,* **33,** 421–440.

ANGELL, J. R., and FITE, W. (1901) The monaural localization of sound. *Psychology Review,* **8,** 225–246.

BATTEAU, D. W. (1967) The role of the pinna in human localization. *Proceedings of the Royal Society, London, Series B,* **1011,** 158–180.

BATTEAU, D. W. (1968) In 'The Neuropsychology of spatially oriented behaviour' Ed. by S. J. Freedman, Dorsey Press, Homewood, Ill., U.S.A.

BLAUERT, J. (1970) Sound localization in the median plane. *Acustica,* **22,** 205–213.

BLOCH, E. (1893) Cited by BORING, E. G. (1942).

BORING, E. G. (1942) Sensation and perception in the history of experimental psychology. Appleton—Century Crofts Inc., N-Y.

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

BOSATRA, A. and RUSSOLO, M. (1976) Directional hearing, temporal order and auditory pattern in peripheral and brain stem lesions. *Audiology,* **15,** 141–151.

BRUGGE, J. F., DUBROVSKY, N. A., AITKIN, L. M., and ANDERSON, D. J. (1969) Sensitivity of single neurons in auditory cortex of cat to binaural tonal stimulation; effects of varying interaural time and intensity. *Journal of Neurophysiology,* **32,** 1005–1024.

CASSEDAY, J. H., and NEFF, W. D. (1973) Localization of pure tones. *Journal of the Acoustical Society of America,* **54,** 365–372.

CASSEDAY, J. H., and NEFF, W. D. (1975) Auditory localization: Role of auditory pathways in brain stem of the cat. *Journal of Neurophysiology,* **38,** 842–858.

EVANS, E. F., and WHITFIELD, I. C. (1964) Classification of unit responses in the auditory cortex of the unanaesthetized and unrestrained cat. *Journal of Physiology,* (London), **174,** 477–493.

FIRESTONE, C. (1930) The phase difference and amplitude ratio at the ears due to a source of pure tone. *Journal of the Acoustical Society of America,* **2,** 260–270.

FISHER, H. G., and FREEDMAN, S. J. (1967) Cited by FISHER, H. G., and FREEDMAN, S. J. (1968).

FISHER, H. G., and FREEDMAN, S. J. (1968) The role of the pinna in auditory localization. *Journal of Auditory Research,* **8,** 15–26.

GALAMBOS, R., SCHWARTZKOPFF, J., and RUPERT, A. (1959) Microelectrode study of superior olivary nuclei. *American Journal of Physiology,* **197,** 527–536.

GARDNER, M. B. (1973) Some monaural and binaural facets of median plane localization. *Journal of Acoustical Society of America,* **54,** 1489–1495.

GOLDBERG, J. M., and BROWN, P. B. (1969) Response of binaural neurons of dog superior olivary complex to dichotic tonal stimuli: Some physiological mechanisms of sound localization. *Journal of Neurophysiology,* **32,** 613–636.

GREENE, T. C. (1929) The ability to localize sound: A study of binaural hearing in patients with tumour of the brain. *Archives of Surgery,* **18,** 1825–1841.

GROEN, J. J. (1969) Diagnostic value of lateralization ability for dichotic tone differences. *Acta Oto-laryngologica,* **67,** 326–332.

GULICK, W. L. (1971) Hearing: Physiology and Psychophysics. *Oxford University Press.*

HALL, J. L. (1965) Binaural interaction in the accessory superior olivary nucleus of the cat. *Journal of the Acoustical Society of America,* **37,** 814–823.

HARRISON, J. M. (1974) The auditory system of the medulla and localization. *Federation Proceedings,* **33,** 1901–1903

HARRISON, J. M., and FELDMAN, M. L. (1970) Anatomical aspects of the cochlear nucleus and superior olivary complex in contributions to sensory physiology. Ed. W. D. Neff. *Academic Press,* New York.

HEFFNER, H. (1978) Effect of auditory cortex ablation on localization and discrimination of brief sounds. *Journal of Neurophysiology,* **41,** 963–976.

JERGER, J. F. (1960) Observation on auditory behaviour in lesions of the central auditory pathways. *Archives of Otolaryngology,* **71,** 797–806.

JERGER, J., WEIKERS, N. J., SHARBROUGH, F. W., and JERGER, S. (1969) Bilateral lesions of the temporal lobe. *Acta Otolaryngologica,* Supplement 258, 23–26.

JONGKEES, L. B. W, and VAN DER VEER, R. A. (1957) Directional hearing capacity in hearing disorders. *Acta Otolaryngologica,* **48,** 465–474.

JONGKEES, L. B. W., and VAN DER VEER, R. A. (1958) On directional sound localization in unilateral deafness and its explanation. *Acta Otolaryngologica,* **49,** 119–131.

KLEMM, O. (1920) Cited by BORING, E. G. (1942).

LABORDE, J. V. (1881) Cited by BORING, E. G. (1942).

LACKNER, J. R. (1973) The role of posture in sound localization. *Journal of Experimental Psychology,* **26,** 235–251.

LIDÉN, G., and KORSAN-BENGSTEN, M. (1973) Audiometric manifestations of retrocochlear lesions. *Scandinavian Audiology,* **2,** 29–40.

MACH, E. (1906) Cited by FISHER, H. G., and FREEDMAN, S. J. (1968).

MALLOCH, A. (1908) Cited by GULICK, W. L. (1971).

MASTERTON, R. B., JANE, J. A., and DIAMOND, I. T. (1967) Role of brainstem auditory structure in sound localization. I. Trapezoid body, superior olive and lateral lemniscus. *Journal of Neurophysiology,* **30,** 341–360.

MATZKER, J. (1959) Two new methods for the assessment of central auditory function in cases of brain disease. *Annals of Otorhinolaryngology,* **44,** 542–555.

MEURMAN, Y., and MEURMAN, O. H. (1954) Do the semi-circular canals play a part in directional hearing? *Acta Otolaryngologica,* **44,** 542–555.

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press

MORE, L. T., and FRY, H. S. (1907) Cited by BORING, E. G. (1942).
MOUSHEGIAN, G., and RUPERT, A. L. (1974) Relations between the psychophysics and neurophysiology of sound localization. *Federation Proceedings,* **33,** 1924–1927.
MUNSTERBERGER (1889) Cited by PIERCE, A. H. (1901).
NILSSON, R., LIDÉN, G., ROSEN, M., and ZOLLER, M. (1973) Directional hearing, three different test methods. *Scandinavian Audiology,* **2,** 125–131.
NILSSON, R., and LIDÉN, G. (1976) Sound localization with phase audiometry. *Acta Otolaryngologica,* **81,** 291–299.
NORDLUND, B. (1962a) Physical factors in angular localization. *Acta Otolaryngologica,* **54,** 75–93.
NORDLUND, B. (1962b) Angular localization: A clinical test for investigation. *Acta Otolaryngologica,* **55,** 405–524.
NORDLUND, B. (1964) Directional Audiometry. *Acta Otolaryngologica,* **51,** 1–18.
PIERCE, A. H. (1901) Studies in auditory and visual space perception. Longmans, Green & Co. (New York).
PREYER and ARNHEIM (1887) Cited by PIERCE, A. H. (1901).
RAYLEIGH, LORD (1877) (1907) Cited by GULICK, W. L. (1971).
SANCHEZ-LONGO, L. P., FORSTER, F. M., and AUTH, T. L. (1957) A clinical test for sound localization and its applications. *Neurology,* **7,** 655–663.
SANCHEZ-LONGO, L. P., and FORSTER, F. M. (1958) Clinical significance of impairment of sound. *Neurology,* **8,** 119–125.
STROMINGER, N. L., and OESTERREICH, R. E. (1970) Localization of sound after section of the brachium of the inferior colliculus. *Journal of Comparative Neurology,* **138,** 1–18.
TERHUNE, J. M. (1974) Sound localization abilities of untrained humans using complex and sinusoidal sounds. *Scandinavian Audiology,* **3,** 115–120.
THOMPSON, S. P. (1878) Cited by GULICK, W. L. (1971).
TONNING, G. M. (1975) Auditory localization and its clinical applications. *Audiology,* **14,** 368–380.
VENTURI (1796) Cited by GULICK, W. L. (1971).
VON KRIES (1890) Cited by PIERCE, A. H. (1901).
WALLACH, H. (1940) The role of head movements and vestibular and visual cues in sound localization. *Journal of Experimental Psychology,* **27,** 339–368.
WALSH, E. G. (1957) An investigation of sound localization in patients with neurological abnormalities. *Brain,* **80,** 222–250.
WILSON, H. A., and MYERS, C. S. (1908) The influence of binaural phase differences in the localization of sound. *British Journal of Psychology,* **2,** 363–385.
WUNDT, F. (1893) Cited by PIERCE, A. H. (1901).

https://doi.org/10.1017/S002221510009037X Published online by Cambridge University Press