



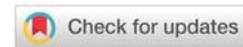
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Research Article

Binaural hearing: Physiological and Clinical View

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Introduction

The main difference between the two ears is that they are not in the same place [1]. Use of both the ears to perceive the world of sound around us is defined as Binaural hearing. Just as we use two eyes to see in three dimensions, we use two ears for “dimensional hearing”. Binaural hearing is literally opposite of monaural hearing. It allows us to (a) ‘map’ the sound in space, (b) pick out soft sounds, (c) pick out distant sound or speech and (d) separate a single voice from surrounding background noise. Among the mammals, human is considered to be the one gifted with most developed communication skill. One of the key factors that empowers him with his communication skill is spatial hearing. Spatial hearing provides cues as to the relative number and location of sound sources and objects in the environment, helps in determining the dimension and characteristics of rooms and enclosed spaces, and contributes to the “cocktail party effect”, whereby the listeners are able to hear out against other interfering voices in crowded listening environments [2]. This article aims to help in understanding how the auditory spatial cues arising from individual outer and inner ears are computed and processed at specialized subcortical centres and lead to binaural hearing.

Physiology

A sound stimulus is distinguished from another by its characteristics of frequency, intensity and time. Thus, two sounds with equal frequency and intensity, originating directly in front of an individual with normal hearing, which arrive at the ears at the same time may be literally indistinguishable from one another. Similarly, sounds with equal frequency, intensity and time, originating directly at the back of an individual with normal hearing, may also be literally indistinguishable from one another.

If there is slightest change in any of these characteristics, the hearing mechanism detects it and reacts to this change on a new bit of information to be analyzed in binaural hearing.

This change could be (a) Inter-aural Time Difference (ITD), (b) Inter-aural Loudness Difference (ILD), (c) Inter-aural Frequency Difference (IFD) and (d) Head Related Transfer Function (HRTF). These changes are analyzed by lower and higher auditory processing system.

a) Inter-aural time difference

The maximum time lag for sound generated at one side of the head is around 0.6 millisecond. A trained ear can detect a time difference as slight as 30 microsecond. ITD is a major factor in localizing lower frequency sounds of <1.5kHz. That means, for many terrestrial mammals (particularly human) localization of sound source in the horizontal plane is achieved by an exquisite sensitivity to difference in fine time structure of low frequency (<1.5kHz) components between the two ears [3]. Though the neurones in both the major nuclei of Superior olivary complex, namely Medial Superior Olive (MSO) and lateral superior olive (LSO) are capable of extracting ITD information from binaural inputs, MSO is considered the major site for ITD analysis in mammals [3].

b) Inter-aural loudness difference

Normal ears use intensity of sound as the most common clue for locating sound sources. The moment a loud sound is heard on one side, a judgment is made that the source of the sound is on that particular side. Judgment is also made about an estimated distance of the source. LSO is considered the major site for ILD analysis in mammals [4].

These two characteristics of time and loudness, are used in binaural hearing to localise the source of sound by (i) frequency based auditory processing and (ii) binaural summation of loudness:-

- i) **Frequency based auditory processing:** British physicist Lord Rayleigh [5], (1907).



separated the auditory spatial processing into (a) low tone processing and (b) high tone processing. Distinguishing between the two, he proposed his “Duplex Theory” and suggested that ITD is the primary cue used to localize positions of low-frequency tonal sources (< 2KHz), while ILD is used for high-frequency tonal sources (>5KHz). Anatomical and physiological studies have revealed two parallel brainstem pathways that appear to encode ITDs and ILDs separately [6]. ITDs are extracted by MSO neurons in which ITD sensitivity results from the coincident arrival of excitatory inputs from the two ears ILDs are extracted by LSO neurons via a subtraction-like process resulting from inhibitory inputs from the contralateral and excitatory inputs from the ipsilateral ear. The dual brainstem pathways provide anatomical and physiological correlates of the Duplex theory.

ii) **Binaural summation of loudness:** Loudness of a sound depends on the number of action potentials triggered by it. It is integrated in brainstem. Each ear contributes substantially to the action potentials that reach the brainstem. The number doubles when the two ears are used instead of one ear for a sound coming from the front of the listener. This is called binaural loudness summation [7]. It is, thus, another measurable dimension associated with binaural hearing. It is common experience that if one is made to block one ear with an ear plug, the loudness of sound coming from a television in front immediately goes down which is restored as the ear is unplugged. It proves that when two ears receive a sound stimulus, the resultant loudness sensation is greater than that occurring with just one ear.

c) Inter-aural frequency difference

Sound travels in waveforms. A sound wave consists of segments of compression and rarefaction. Number of cycles of compression and rarefaction occurring in a pure tone is defined as frequency. The sound waves reach the ears either ‘in phase’ or ‘out of phase’. If the compressions of the waves of two pure tone signals arrive at the ears at the same time, they are said to have been ‘in phase’. Whereas if a compression wave arrives at one ear at the same time when a rarefaction wave arrives at the other ear, the two pure tone signals are said to have been presented ‘out of phase’. A pure tone is received by the two ears either in phase or out of phase depending on the frequency and a complex sound tone is received by the two ears in both phases.

Laboratory studies by Joris PX et al have already demonstrated the excellent, and often enhanced (relative to their auditory nerve inputs), phase-locking abilities of globular and spherical bushy cells of the cochlear nucleus that provide the inputs to the Medial Nucleus of Trapezoid Body (MNTB) and the ipsilateral inputs to the LSO [8]. Tollin et al also examined whether low-characteristic-frequency LSO and MNTB neurons exhibit phase-locked responses to pure-tone stimuli. They proved that when stimulated with a characteristic frequency tone presented to the ipsilateral and contralateral excitatory

ear, the LSO and MNTB neurons respectively exhibits a high degree of phase locking [9].

d) Head related transfer function

Between the two ears, head acts as an effective acoustic block, reflecting and diffracting the sounds whose wavelengths are smaller compared to the dimensions of head. Depending on frequency, the sound pressure presented to the ears on either side of the head differs. The difference is related to the location of the sound in the free field. This inter-aural level differences is most significant for high frequencies.

A listening environment comprises of ever changing complex sounds. It challenges us to analyse and process the slightest differences in the ever changing complex acoustic signals in order to achieve a good binaural hearing. The differences in these clues are further heightened by head movement by altering the relative intensity, time of arrival and the phase of acoustic signals at each ear. The head movement aided by reflection of sounds from pinna results in localization of sources and is described as ‘Head Related Transfer Function (HRTF)’. So, HRTF is the direction dependent filtering effect of head and pinna.

Whether the sound source is located in the front or at the back, is not uniquely determined by time difference. It is rather determined by the pinna which reflects the sound differently for different positions of sound source in a listening atmosphere.

A “Cone of confusion” also exists at each side of the head creating localization ambiguities for points located on the circumference of the cone. This cone is centred on the interaural axis with apex of the cone being the centre of the head. A sound source positioned at any point on the surface of the cone of confusion will have the same ITD values making sound localization difficult [10].

To determine the source location in vertical plane, front or back, the binaural cues of ITD, ILD and IFD fall short of perfection. The auditory system, in addition to binaural cues, hence also exploits HRTF. These spectral cues for localization underpin the ability to disambiguate the so-called cone of confusion, resolving sources in front from those behind as well as determining their elevation, a task not possible using binaural cues alone [11].

Besides these effects of ITD, ILD, IFD and HRTF, we also have the capability of central nervous system (CNS) to process the slightly different auditory inputs arriving from the two ears utilizing two important phenomena, namely Binaural squelch and Binaural redundancy.

i) **Binaural squelch:** If two sound sources, one giving target signal and the other noise, are sited at the same place and their intensity well adjusted, the target signal will be effectively masked by the noise. When the noise source is moved to a different place, the target signal may become audible again, which indicates a release from masking in relation to spatial separation of the two sources. This effect is called binaural squelch, and is also known as binaural unmasking or Hirsh effect [12].



This phenomenon helps the listener when he is receiving diotic sounds (dichotic sounds are the sounds heard independently by each ear) in any noisy environment e.g. coffee house, party, auditorium etc. In such environment, CNS is able to suppress the interfering noises while focusing on the speech of just one person by binaural selectivity. This allows better communication in noisy environments.

ii) Binaural redundancy: When the listener is receiving dichotic sounds, both ears send auditory information to the brain independently. Brain, acting as the central processor upon these dissimilar information arriving from each ear, perceives it much better than each ear separately. The listener gets the benefit of fusion of these information arriving from two ears separately and is able to filter out unnecessary parts of information by making them redundant. He not only perceives the sound signals louder, but is also able to understand the speech better. Binaural redundancy actually results in binaural enhancement. The effect of binaural redundancy refers to the improvement in speech reception when the same signal and noise are audible in both ears rather than in one ear alone [13].

These two CNS phenomena, namely Binaural squelch and Binaural redundancy, associated with binaural hearing are attributed to the rich neural connections crossing over from right ear to left cerebral hemisphere and left ear to right cerebral hemisphere and also to the neural fibres connecting the two hemispheres.

Mechanism of binaural hearing

The following sequence of events happen ultra fast in binaural hearing:-

- a) Auditory signal reaches the ears.
- b) Reflections from pinna and head movement assist the listener to appreciate the direction of source and its distance.
- c) Inter-aural time/frequency/intensity/phase differences are analyzed by lower auditory system to have a better appreciation of direction, loudness and pitch as well as separating the sound sources.
- d) Binaural squelch and binaural redundancy/enhancement give the listener a selective enhanced hearing and better understanding of speech.

Pathological correlates

Unilateral hearing loss or asymmetric bilateral hearing loss is literally equivalent to absence of good binaural hearing. This disadvantage puts a person under lot of strain. In any simple listening situation where the speech and noise are coming from different sources and are in obvious conflict with each other, the person loses the ability to filter out speech from noise.

The level of disability caused by hearing loss is mainly

determined by the hearing in the better hearing ear as assessed by pure-tone audiometry. Rehabilitation is required in these cases where a disability loss in the better ear is above 40dB hearing level (HL). In ideal situation with no cost issues, the patients should be habilitated by binaural fitting of hearing aids expecting them to extract the benefit of accurate localization, adequate segregating of competing sounds and better speech intelligibility. Although, in these patients and in the recipients of cochlear implants, significant asymmetry may continue to appear across the frequency range over a long period of time. In these patients, after years of having to process asymmetric inputs neural circuitry may have been affected by plasticity so that time and training may be needed before binaural advantages recover [14].

Fitting of binaural hearing aids should be such that aim to optimise the delivery of acoustic information and also to preserve the spatial cues. Similarly, bilateral cochlear implants fitted to deserving candidates should also aim to fulfil the above two objectives as well as provide improved use of signal to noise ratio at the two ears.

Advantages of binaural hearing

- 1) Since the brain can focus on the conversation the listener wants to hear, binaural hearing results in better understanding of speech.
- 2) Better sound and speech discrimination improves speech intelligibility in difficult listening situations leading to improved social communication.
- 3) It provides better ability to localize the sound and better detection of sounds coming from every direction in all situations.
- 4) By providing better sound quality, with 360 degree range of sound inputs, binaural hearing provides better sense of balance and sound quality.
- 5) With binaural hearing, there is summation of intensity of sound, hence hearing requires less loudness. Less loudness means less distortion and better tonal quality.
- 6) A voice that is barely heard at 10 ft with one ear can be heard upto 40 ft with two ears. A person can hear sounds from a farther distance.
- 7) Binaural hearing keeps both the ears active, without auditory deprivation for any ear.
- 8) Binaural hearing is less tiring and listening is more pleasant. There is no strain, hence it is relaxing experience.
- 9) Binaural hearing results in a feeling of balanced reception of sounds, also known as stereo-effect; whereas monaural hearing creates an unusual feeling of sounds being heard in one ear.
- 10) Less loudness is required in binaural hearing; resulting in better tolerance of sounds.



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