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**ABSTRACT**

**INDEX TERMS**

**I. INTRODUCTION**

hearing loss is one of most prevalent health issues in older life[1]. WHO has reported that 403 million people worldwide lives with moderate or severe hearing loss. Out of these 403 million people, 127.1 million are from the Western Pacific, 103.4 million are from South East Asia, 58.8 million are from the Americas, 52.8 million are from Europe, 38.7 million are from Africa, and 21.3 million are from the Eastern Mediterranean[2].

According to the National Aboriginal and Torres Strait Islander Health Survey (NATSIHS), around 82% of Indigenous Australians aged 55 or older had hearing loss[3]. According to another study, hearing loss is significantly more common among people of Pacific or Maori origin in New Zealand than it is among people of other races[4].

According to the Global Burden of Disease (GBD) Study, 1.57 billion individuals worldwide suffer from hearing loss, with people 50 and older making up 62.1% of this population. The number of persons with hearing loss is expected to reach 2.45 billion by 2050 with increase in global population[5].

Binaural Hearing is the ability of humans to comprehend the information contained in pressure waves arriving at the two cochleae of ears [6].  Binaural hearing plays a crucial role in traversing through the auditory environment[7]. The first research conducted by Venturi(1976)  proved that ability to localize audio sources is the result of interaural level difference (ILD) [8]. Rayleigh demonstrated that in addition to ILD the difference between the arrival of the sound at both ears namely interaural time difference (ITD) is an important cue for auditory sours localization[9].

It is important to note that ITD and ILD cannot be used individually for source localization. The single value of ILD or ITD does not specify a single direction but a cone of directions. Sound in the medial plane arrives at the ears with no interaural variation which means sound localization needs other signals. It is necessary to have additional information like acquiring multiple direction samples by moving the head and acquiring frequency information obtained through sound filtering by torso, head, and reverberations to Identify the extract location of the source in the cone of directions[10].

The ability to discriminate the sound location was investigated in 1958. In this experiment the ability of the subject to differentiate between the sounds of loudspeakers placed at different locations in an anechoic chamber. Results of the experiment were analyzed in terms of minimum audible angle (MMA) which is the minimum difference between azimuths of identical sound sources. It was concluded that MMA is dependent on both frequencies in sound and location. The table shows accepted values of MMA for different sound sources[11], [12].

**Research Methodolgy**

**Reseach questions**

The following questions will be addressed because of this investigation:

1. What are the acoustic cues for sound source localization?
2. What is Importance of Binaural pathway and impairments ?
3. What are the methods of characterizing binaural hearing loss?
4. What are objective psychological measures for characterizing binaural hearing loss under the BMLD paradigm
5. Is there any correlation between behavioral BMLD and AEP methods?
6. Which is the best AEP analysis method for the BMLD paradigm?

**DATA SOURCES**

In order to locate relevant literature, the following academic

Repositories were consulted:

1. Google Scholar
2. Elsevier
3. IEEE Xplore
4. Science Direct
5. Springer
6. Pubmed

**Description of the material being examined**

Articles that did not adhere to the aforementioned standards were all disqualified, as were any that did not explicitly outline the methodology's parameters or the study's limits. Three steps made up the screening process. First, two separate researchers used matching descriptors to select articles from each database that had been located through a search. Next, article titles were examined, and last, article abstracts were examined. Eventually, publications that met the inclusion requirements were chosen.

**INCLUSION AND EXCLUSION CRITERIA**

The results of the internet search were then refined using the properly thought-out criteria for inclusion andexclusion. . Downloads were made of all the papers that satisfy the following requirements.

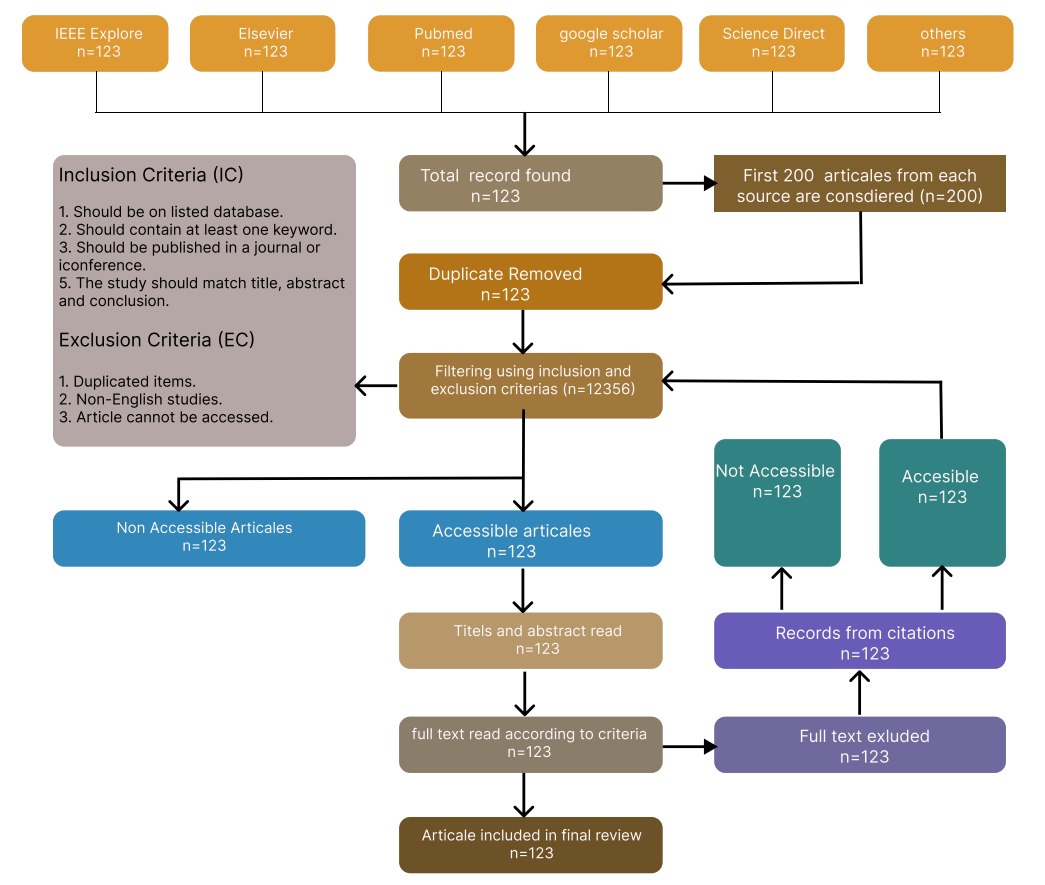
Inclusion Criteria (IC)

1. Should be on listed database.
2. Should contain at least one keyword.
3. Should be published in a journal or in a
4. conference.
5. The study should match title, abstract and
6. conclusion.

Exclusion Criteria (EC)

1. Duplicated items.
2. Non-English studies.
3. Article cannot be accessed.

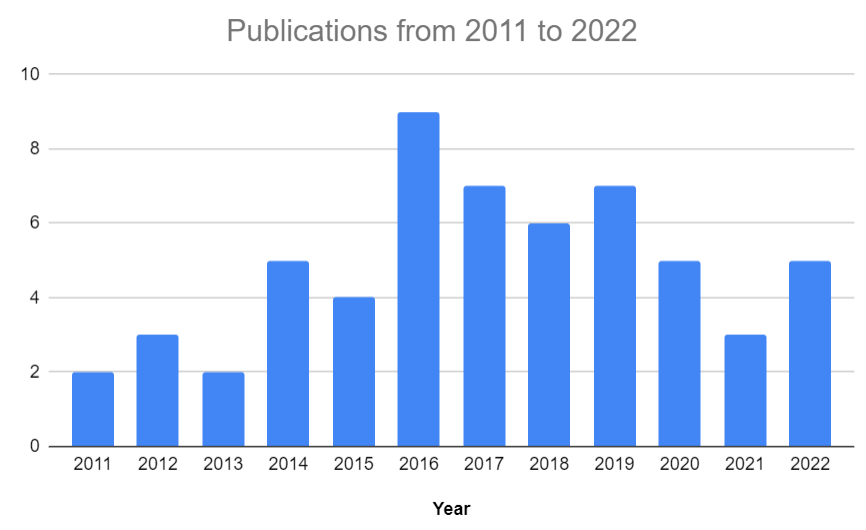
we searched the web archives. The term "masking level diffrecine" refers to ad diffrerne name   names like  binural masking level  differnce ,Masking Level  , same is the case with names of AEPS, . Therefore, the search was specifically designed to return information on all different term used for same phnomenan.



There were chosen a total of x scientific studies, comprising journal and conference papers. We utilized only the first x results from the aforementioned data sources which were the most pertinent. Our dataset has x  publications in total.

The list has been updated to eliminate all redundant entries.

29 papers are unavailable to us, and they have been deleted.Sfter reading the titles and abstracts, the ones that aren't pertinent to this study are eliminated.Scientific journals received more attention than conference publications. If the literature supports this study, it was included to the collection of literature; if not, the paper was abandoned.This reduced the total to x publications.The papers that don't offer any novel concepts, don't use them, or content  that was very basic and general were eliminated. Ultimately,the total number of articles was lowered to 47 when the complete content was evaluated.  The remainder pieces of writing were carefully examined and used to respond to our research queries.



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| --- | --- | --- | --- | --- |
| Type | Date | Author | Journal/Confernce Name | Library |
| JA | 2022 | Pöntynen, Henri; Salminen, Nelli | Journal of Neurophysiology | Springer |
| JA | 2022 | Xu, Zihao; Bai, Yanru; Zhao, | Clinical Neurophysiology | ScienceDirect |
| JA | 2022 | Deliano, Matthias; Seidel, Peggy; Vorwerk, Ulrich; | Methods | ScienceDirect |
| JA | 2022 | Borjigin, Agudemu; Hustedt- | eNeuro | PubMed |
| JA | 2022 | Lertpoompunya, Angkana; Ozmeral, Erol J.; Higgins, | Journal of the Association for Research in Otolaryngology | Pubmed |
| JA | 2021 | Geravanchizadeh, Masoud; Zakeri, Sahar | Trends in Hearing | PubMed |
| JA | 2021 | M Geravanchizadeh, S Zakeri | PLoS ONE | IOPscience |
| JA | 2021 | Watson, Sam; Laugesen, Søren; Epp, Bastian | Journal of Neural Engineering | PubMed |
| JA | 2020 | Koerner, Tess K.; Muralimanohar, Ramesh | Frontiers in Neuroscience | Frontiers |
| JA | 2020 | Baker, D.H., Vilidaite, G., | Scientific Report | nature |
| JA | 2020 | Balkenhol, Tobias; | NeuroImage | PubMed |
| JA | 2020 | Ungan, Pekcan; Yagcioglu, Suha; Ayik, Ece | Brain Research | ScienceDirect |
| JA | 2020 | Smieja, Daniel A.; Dunkley, Benjamin T.; Papsin, Blake C.; | Frontiers in Neuroscience | ScienceDirect |
| JA | 2019 | Brown, Andrew D.; Anbuhl, Kelsey L.; Gilmer, Jesse I.; | Frontiers in Neuroscience | PubMed |
| JA | 2019 | Polonenko, Melissa J.; Papsin, | Journal of Neurophysiology | ScienceDirect |
| JA | 2019 | Kubota, Toshinori; Ito, Tsukasa; Abe, Yasuhiro; Chiba, | Hearing Research | Springer |
| JA | 2019 | Gnanateja, G. Nike; Maruthy, Sandeep | Journal of Neurophysiology | ScienceDirect |
| JA | 2019 | Ozmeral, Erol J.; Eddins, David A.; Eddins, Ann Clock | [Journal of Neurophysiology](https://journals.physiology.org/journal/jn) | PubMed |
| JA | 2019 | Ungan, Pekcan; Yagcioglu, Suha; Ayik, Ece | Experimental Brain Research | Springer Link |
| JA | 2019 | Zhang, Xiaochen; Gong, Qin | Hearing Research | PubMed |
| JA | 2018 | Anderson, Samira; Ellis, Robert; Mehta, Julie; Goupell | Journal of Neurophysiology | PubMed |
| JA | 2018 | Easwar, Vijayalakshmi; Yamazaki, Hiroshi; Deighton, | Trends in Hearing | Springer |
| JA | 2018 | Vercammen, Charlotte; Goossens, Tine; Undurraga, | Brain Topography | PubMed |
| JA | 2018 | Wang, Qian; Lu, Hao; Wu, Zhemeng; Li, Liang | Trends in Hearing | ScienceDirect |
| JA | 2018 | Van Eeckhoutte, Maaike; Spirrov, Dimitar | Hearing Research | PubMed |
| CP | 2018 | Dai, L., Best, V., & Shinn-Cunningham, B. G | Proceedings of the National Academy of Sciences | PubMed |
| JA | 2017 | Gransier, Robin; van ; | Ear and Hearing | PubMed |
| JA | 2017 | C Vercammen, A van Wieringen | The European Journal of Neuroscience | PubMed |
| JA | 2017 | Bednar, Adam; Boland, Francis M.; Lalor, Edmund C. | Ear and Hearing | PubMed |
| JA | 2017 | A Bednar, FM Boland, EC Lalor | International Journal of Audiology | Wiley |
| JA | 2017 | Marsella, Pasquale; Scorpecci, Alessandro; Cartocci, Giulia; | International Journal of Pediatric Otorhinolaryngology | ScienceDirect |
| CP | 2017 | Van Eyndhoven, Simon; Francart, Tom; Bertrand, | IEEE transactions on bio-medical engineering | PubMed |
| JA | 2017 | Small, Susan A.; Ishida, Ieda M.; Stapells, David R. | The European Journal of Neuroscience | PubMed |
| JA | 2016 | Laumen, Geneviève; Tollin, Daniel J.; Beutelmann, Rainer; | IEEE Engineering in Medicine and Biology Society | ScienceDirect |
| JA | 2016 | Cevallos-Larrea, Pablo; Pereira, Thobias; | Hearing Research | PubMed |
| CR | 2016 | Tirth R. Patel, Antoine J. Shahin, Jyoti Bhat, D. Bradley | Annals of Otology, Rhinology & Laryngology | PubMed |
| JA | 2016 | Undurraga, Jaime A.; Haywood, Nick R.; Marquardt, Torsten | Physiology, Psychoacoustics and Cognition in Normal and Impaired Hearing | PubMed |
| JA | 2016 | JA Undurraga, NR Haywood | [Journal of the Association for Research in Otolaryngology](https://link.springer.com/journal/10162) | springer |
| JA | 2016 | Jafarpisheh, Amir Salar; Jafari, Amir Homayoun; Abolhassani | Journal of Neural Engineering | Springer |
| JA | 2016 | Ozmeral, Erol J.; Eddins, David A.; Eddins, Ann C. | Journal of Neurophysiology | PubMed |
| CP | 2016 | Hu, Hongmei; Kollmeier, Birger; Dietz, Mathias | JARO: Journal of the Association for Research in Otolaryngology | Springer Link |
| JA | 2016 | Das, Neetha; Biesmans, Wouter; Bertrand, Alexander; | Journal of Neural Engineering | IOPscience |
| JA | 2015 | Haywood, Nicholas R.; Undurraga, Jaime A.; | Clinical Neurophysiology | PubMed |
| JA | 2015 | Cai, Yuexin; Zheng, Yiqing; Liang, Maojin; Zhao, Fei; Yu, | Hearing Research | PubMed |
| JA | 2015 | Papesh, Melissa A.; Billings, Curtis J.; Baltzell, Lucas S. | Trends in Hearing | ScienceDirect |
| JA | 2015 | Ikeda, Kazunari | PLoS ONE | ScienceDirect |
| JA | 2014 | Mohebbi, M., Mahmoudian, S., Alborzi, M. S., Najafi-Koopaie | American Journal of Audiology | PubMed |
| JA | 2014 | Ahadi, Mohsen; Pourbakht, Akram; Jafari | Hearing Research | Springer |
| JA | 2014 | Ross, Bernhard; Miyazaki, Takahiro; Thompson, Jessica;o | Journal of Neurophysiology | PubMed |
| JA | 2014 | Ross, B., Miyazaki, T., Thompson, | Journal of Neurophysiology | PubMed |
| JA | 2014 | Ahveninen, Jyrki; Kopčo | Auris Nasus Larynx | ScienceDirect |
| JA | 2013 | Senkowski, Daniel; Pomper, Ulrich; Fitzner, Inga; Engel, | Hearing Research | PubMed |
| JA | 2013 | Epp, Bastian; Yasin, Ifat; Verhey, Jesko L. | Human Brain Mapping | ScienceDirect |
| JA | 2012 | Hansen, Erin E.; Small, Susan A. | Journal of the Association for Research in Otolaryngology | IOPscience |
| JA | 2012 | Grose, John H.; Mamo, Sara K. | Ear and Hearing | PubMed |
| JA | 2012 | Poelmans, Hanne; Luts, Heleen; Vandermosten, | Ear and Hearing | PubMed |
| JA | 2011 | Rosner, Thomas; Kandzia, Florian; Oswald, Johann A.; | Brain Research | PubMed |
| JA | 2011 | Zhang, Fawen; Deshpande, Aniruddha; Benson, Chelsea; | The Journal of the Acoustical Society of America | ScienceDirect |
|  |  |  |  |  |

1. ***Binaural hearing Pathway and impairments***

Psychoacoustical methods to analyze binaural hearing were initially investigated to understand anatomy and physiology[12], [13]. Figure 1 illustrates the currently accepted ascending binaural hearing physiological auditory pathway. Stecker and Gallun identified (1) VCN, (2) SOC, (3) NLL, (4) IC, and (5) AC as five potential sites for interaural binaural processing[14].

As illustrated in Figure 1, there are numerous locations throughout the pathway where impairment could cause binaural hearing loss. At the start, auditory signal transmission can be affected if there is any damage to auditory nerves or if synapses are not properly functioning. The next possible cause can be damage to CN or improper functioning of the transmission pathway to the trapezoidal body, which can delay the neural impulses to introduce errors in audio source localization. In addition, improper functioning of NLL, IC, MGB, and AC can result in errors in the transmission of binaural information for audio source localization.

High-fidelity transmission via the medial and lateral nuclei of the trapezoidal body from the outer ear to LSO and MSO is crucial for the proper operation of this binaural system because LSO and MSO depend on precision in microseconds for the analysis of neural impulses from both ears. LSO and MSO neurons' discharge rates can fluctuate between maximum range with only a 1-millisecond difference between the input signals of both ears.

Essential Accuracy for the Binaural system which is sensitive to a minimum ITD of 10 microseconds depends on the ability which transforms instantaneous pressure at the eardrum to auditory neural impulses known as Neural phase locking (NPL)[15]. Hence any disease such as MS which harms Neural phase locking can cause binaural impairment.

Conductive hearing loss is a failure in the conversion of air pressure to fluid motion in the cochlea. It can cause distortion in NPL which results in binaural analysis error. Damage to any part of the cochlea itself can result in a reduction of NLP accuracy, this impairment is referred to as sensorineural hearing loss (SNHL). Impairment due to damage to any site along the binaural hearing pathway beyond the cochlea is called retrocochlear hearing loss (RHL)[7].

**Measures for Binaural hearing Loss**

Contrary to objective procedures, subjective ones demand active participation from the subject. They are crucial for determining auditory perception and comprehension in noisy environments. It is impossible to evaluate quality of life and perceptual deficiencies impartially. Audiometry under competition and frequency discrimination tests are the two most popular subjective techniques for evaluating auditory discrimination. Reproducibility over the long term is one restriction.

The earliest approach to measuring the audio sources localization ability of subject sounds was produced from one of eighteen audio sources and subjects were asked to point in the direction of the source with their eyes closed[16]. Subjects were categorized into two categories “normal localization ability” and “pathological localization ability” by comparing their response with the response of subjects from another group having no known hearing impairments[17].

An approach developed in 1958 used two-alternative forced choice (2AFC) was utilized to assess the MAA in the horizontal and vertical planes by an array of audio sources in an anechoic environment[12]. These early methods were able to measure sound localization ability, however, these methods failed to characterize the effect of acoustics cues like ILDs and ITDs independently.

A custom device with the ability to change ITD by changing the speed of signal through a fixed length tube by adjusting the water column length in the tube. Exact ITD cannot be measured with this setup, however relative difference concerning normal ITD can be calculated. Signal attenuation at the ears allowed ILD manipulation to establish abnormal sensitivity.

The Just Noticeable Difference (JND) in acoustic cues was first measured in 1983 by adjusting the difference between hearing thresholds with stimulus equal to sensation level[17].

One of the most prominent measures of binaural masking level differences was developed in 1948 by Hirshin[18] [19]. He demonstrated how altering the ITD of either tone or noise influences the precision of recognizing tone in the presence of noise presented through earphones. In the presence of noise, binaural unmasking is the estimated relative detection threshold for the monaural or binaural presentation of tone with frequency changing between 200 and 500 Hz. BMLD for 500Hz tone was gathered for the first time, and it has been most prominent in subsequent works as a speech target comparison[20].

A method for behavioral testing of binaural processing that involves the spatial release of masking like BMLD was proposed which involves a loudspeaker array. In this approach, target audio and masking audio are provided from several locations with variable sound interference[21]. These methods were restricted by the fact that when the masker was presented in a single place, the signal-to-noise ratios (SNRs) at the two ears were different. This resulted in improved performance even in the absence of binaural sensitivity[22], [23].

Another method, like the BMLD, for detecting interaural phase differences was presented. In this procedure, the individual is instructed to report directly on their binaural perception rather than identifying a signal in the noise. This experiment involved playing a static tone to one ear and a frequency-modulated tone to the other. It was discovered that people with normal hearing can detect frequency modulated tones with lower modulation indexes when the FM caused interaural phase differences as opposed to when the same FM was presented monaurally[24].In an extension of this method, FM modulated tones were presented dichotically[25].

Researchers have examined neurophysiological responses in addition to behavioral methods since the emergence of technologies to capture electrical and magnetic brain responses. Dichotic signals are found to induce different neurophysiological reactions than diotic signals[26]. MEG data were used to assess auditory evoked brain response. P1-N1-P2 peaks in AEP were measured to estimate binaural alterations in the middle of the signal[27].

In recent research auditory steady stated response is used for frequency domain analysis for characterization of binaural function. Magnitude response is utilized to measure the correlation between ASSR and changes in binaural configuration [23],[24].

Diagram

Description automatically generated

Table

Description automatically generated

**BMLD TEST paradigm**

BMLD was first presented in 1951 by webster .it is the most frequently employed method for the assessment of intermural acoustic cues[30]. BMLD test is based on the behavioral detection of tones in presence of noise using homophasic and antiphasic masking conditions. it has been illustrated by the researcher that subjects with hearing loss have lower BMLD when compare to the BMLD of the subject with normal hearing [31], [32].

The BMLD is calculated by comparing two conditions. In the homophasic condition, an identical signal with no interaural difference is applied to both ears whereas in the antiphase condition and out phase signals are applied to both ears. The interaural difference for unmasking in antiphasic conditions results in a relatively lower detection threshold.

The BMLD in dB is computed by subtracting the detection threshold in antiphasic from the detection threshold in homphasic and greater unmasking is associated with higher dB values.

**Stimulus Effects on the BMLD**

BMLD can be measured against many types of stimuli like tones and words and clicks. BMLD can be affected by the type of noise, frequency of stimuli, level of the mask, and bandwidth of the mask[30].

The amplitude of the BMLD is affected by the type of masking noise used, and it has been demonstrated that the BMLD achieved with burst masking noise is less than that acquired using continuous masking noise[33].

BMLDs are robust at lower frequencies, with a 15 dB sensitivity at 1 kHz and a 3 dB sensitivity above 15 kHz[34].

The BMLD increases more rapidly as a function of IPD and achieves a higher magnitude when compared to a magnitude change in BMLD caused by a change in noise IPD. As a result, increasing the signal IPD 0 to pi results in a high magnitude of BMLD[35].

It was also concluded that under both antiphasic SoNpi or SpiNo, adding a time delay in any of the two noise channels would result in a drop in BMLD[36].

BMLD increases with the increase in the intensity of the masker from 50 dB to 100 dB [20]. Even at greater intensities, a similar connection between BMLD and masker intensity level has been observed in subjects with hearing loss[37].

All the frequencies in a wideband masker are not equally effective for signal masking in binaural processing. The masker frequencies which are closer to the frequency of the signal are more effective[34].

Subjects with hearing loss had far lower BMLDs in wideband noise than in narrowband noise for a 500 Hz tone[38]. However, when BMLD in adults and children was evaluated in relation to masker bandwidth, it was established that BMLD in children under the age of 7 years is substantially lower for 20 Hz wideband noise than for 320 Hz wideband noise[39].

The behavioral BMLD improves as modulation depth increases. Changes in the amplitude of a narrowband masker or intensity modulation of a wideband noise make signal detection relatively difficult in the homophasic condition, although signal detection in the antiphasic condition is dependent on the subject[40], [41].

A study revealed an improvement in signal detection under homophasic conditions with decreasing noise fluctuations. However, the modulation depth of noise has no influence on the antiphasic masked threshold in some subjects while improving in others[42].

|  |  |  |
| --- | --- | --- |
| author | parameter | finding |
| McFadden[20] | Signal/ Masker | BMLD is observed when an identical masker is added to the non-signal ear, resulting in the SmN0 |
| Yost[43] | Signal Frequency | Lower signal frequencies have a larger BMLD than higher signal frequencies. |
| Durlach & Colburn[35] | IPD | When the polarity of either the signal or the masker is 180 degrees out of phase, the BMLD value is the highest. |
| Colburn & Durlach[35] | ITD | IT varied frofm 0-9ms largest BMLD prodecued at 1ms ITD in |
| Colburn & Durlach[35] | ILD | The BMLD increases with increasing ILD and decreases with increasing noise ILD. |
| Durrant and Nozza[44] | Masker Intensity | As the masker intensity level increases, from 50 to 100 dB SPL, the BMLD rises. |
| Moore [34] | Masker Bandwidth | Signals can be effectively masked by using masker frequency components around the signal frequency. |
| Bernstein & Trahiotis[45] | Signal duration | The differing ways that signal duration affects the BMLD may indicate that low- and high-frequency sounds are processed by various binaural systems. |
| Kohlrausch[46] | Masker duration | For low-frequency signals, a reduction in masker duration from 500 to 25 ms lowers the BMLD value. |
| Eddins & Barber[41] | Modulation | behavioural BMLD grows with depth of noise modulation . |

**Which is the best AEP analysis method for measuring binaural hearing loss**

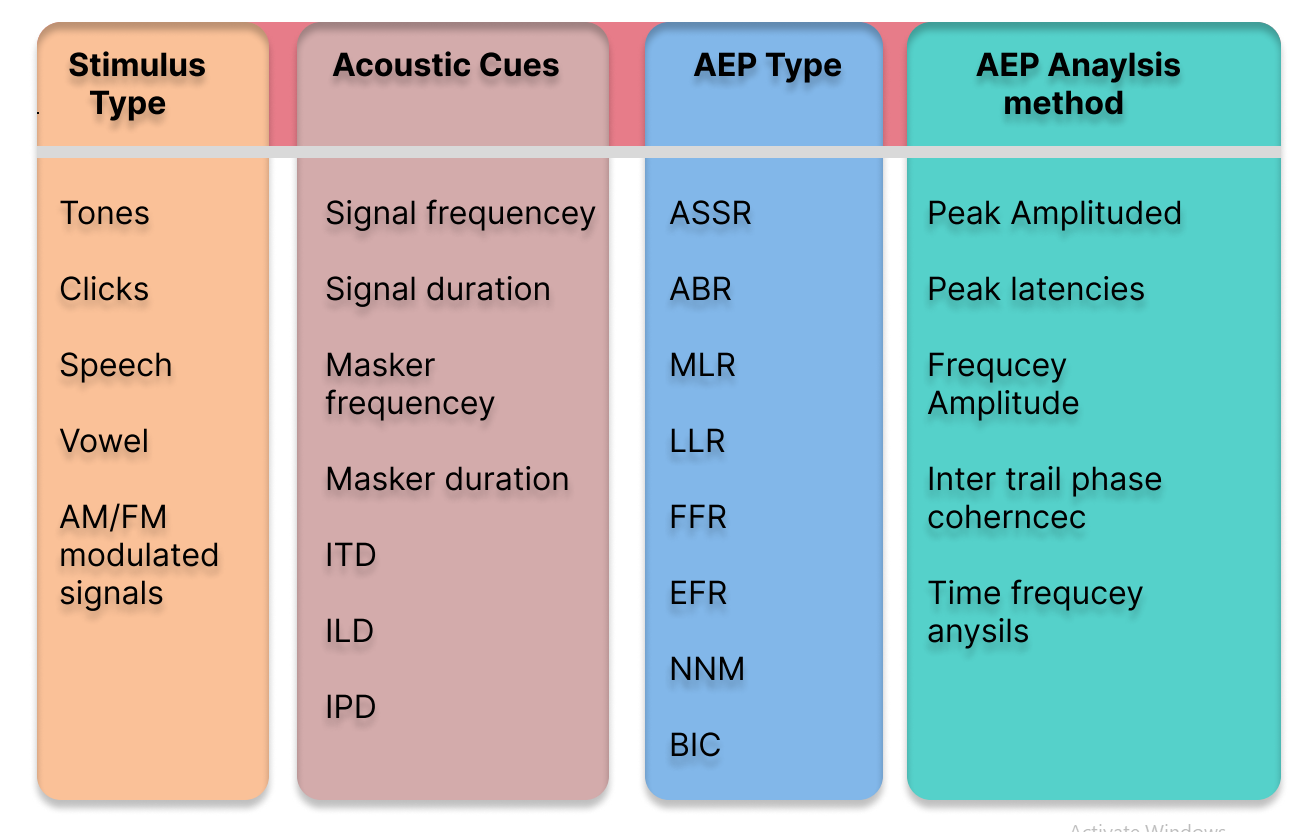
Auditory perception is evaluated using objective methods without the subject's active participation. They include functional MRI (fMRI), positron-emission tomography coupled to CT (PET-CT), functional near-infrared spectroscopy (fNIRS), and cortical auditory evoked potentials as supplements to subjective approaches (CAEP)[47].

In this section we will present different analysis methods for AEP in BMLD test paradigm for binaural hear loss detection. These methods are based on temporal characteristics, frequency domain features or joint time frequency features of AEP produce by different stimulus signals.

ABR is one of the most commonly utilized auditory evoked potentials for threshold determination.[48].

The instantaneous energy of the ABR wave's peak V has been successfully utilized to distinguish between normal and impaired hearing people.[49]

Peak V of ABR is crucial in determining a person's hearing level because it becomes prominent s only at the lower stimulus intensities[50] . In one study, matching filters were used to predict peak V latency of ABR, and statistical significance was demonstrated for estimating hearing loss.[51].Nerual network are also used in research for the estimation of peak V[52].A feedforward neral network and Support vetor machine achived 75.6% and 97% classification accuracy respectively for ABR detection[53], [54].



Temporal processing of AEP

Using a sophisticated new method, larger cerebral reactions to binaural beats can be achieved. Binaurally delivered tones are identical in frequency and opposing polarity. The tone in one ear is increased by 20 Hz at a rate of 1 per second for a period of 20 msec , while the tone in the opposite ear is dropped by the same amount. A 20 msec pulsatile binaural beat is the result of this. The delayed AEPs elicited by this stimulus include reactions to the beat and the monaural frequency shifts[55].

Human frequency perception is based on Von Bekesy's travelling wave and neural phase locking, two physical phenomena. Former causes a certain portion of the basilar member to respond to a specific sound frequency and is, thus, coded in terms of the greatest activation zone on the basilar membrane. The central nervous system uses topographic maps and labelled lines to connect the basilar membrane location of the source of its activation[56].

Later physical events involve neurons (or clusters of neurons) locking themselves to a specific phase of sound, after which the sound's frequency is time-coded. The central nervous system calculates the neuronal activity's autocorrelation. Only frequencies below 2 KHz experience this neuronal phase locking[56].

The basilar membrane hair cells can track audio frequencies as far as human hearing allows. They do this to produce the cochlear microphonic. Afferent neurons can only accurately follow sounds up to their maximal discharge rate, which is a few hundred hertz. But it's possible for a single neuron to react every second,. Thus, populations of neurons may be capable of tracking sounds up to roughly 2KHz and producing a "neurophonic." Both primary neurons and auditory brainstem neurons may contribute to the generation of this neurophonic[57], [58]. EEG can be used to record both the microphonic and the neurophonic  responses which is known as Frequency following response[59]. This EEG was produced by various areas of the auditory system, with responses arriving in the pontine and midbrain regions between 2 and 3 msec and 5 and 7 msec, respectively. Low-frequency hearing thresholds can be evaluated and assessed using FFR[60].

FFR is a representation of the temporal data that could be used to analyse periodicity and pitch. The FFR may not precisely capture all of the observed pitch information in complex stimuli, hence it is unclear how exactly it relates to pitch perception. The pitch perception needs a cognitive choice regarding  temporal aspects can be best perceived, notwithstanding the necessity to represent and analyse the temporal features of sounds[61].

The AEPs to binaural clicks have been examined in numerous investigations.

Finding the differences between the responses to a binaural click and a monaural click is a straightforward strategy. Instead of two stimuli, the binaural stimulus is seen . The brainstem registers this "binaural merger." The ABR to a binaural stimulus and the total of the monaural responses captured when the stimuli are presented to each ear individually, however, differ only slightly. The binaural interaction component is investigated as the slight discrepancy between the binaural waveform and the total of the monaural responses[62].

When the response to a binaural stimulus is comparable to the response to a single monaural stimulus, the effects of binaural fusion are more pronounced in the MLR and LLR  Instead of processing sounds according to the ear or ears in which they are received, the cortex appears to do so[63].

There are two techniques to research how the human brain reacts to quickly varying noises. The simplest method is to simply keep track of steady state reactions to stimuli provided at various frequencies . Tracking the response to a moving stimulus rate is the second [64]. The response is clearly improved by both methods at frequencies about 40 Hz[65] .

If the shift in the interaural phase of low-frequency binaural sounds occurs at the null point of a continuing amplitude modulation, then clear N1-P2 responses can be captured. Young, middle-aged, and elderly persons' magnetic reactions to this stimuli have all been documented. Young subjects can recognise the response with carrier frequencies up to 1250 Hz, whereas older ones can only record it up to 760 Hz. There was no discernible reaction from middle-aged participants to carrier frequencies above 940 Hz, showing that our binaural timing skills start to deteriorate around midlife[27].

It was discovered that the magnitude of the human auditory cortex's reaction to a pause between two rapid noise bursts reduced with age. These physiological alterations were connected to a diminished capacity of perception to identify the gap.

In middle age, both the physiological and the perceptual changes started. Similar to this, as humans age, the AEPs to brief interruptions in a continuous noise are significantly reduced[66]. Another study revealed that even when the stimuli do not elicit any discernible MMN when left unattended, the elderly may still identify occasionally brief gaps from those without gaps (and produce the P3 waves associated with the discrimination)[67]. These outcomes, according to the authors, are the result of top-down compensatory mechanisms for age-related impairments in automatic sensory appraisal.

Human responses after ageing are profoundly impacted. With ageing, the FFR's amplitude falls noticeably, yet these changes happen independently of how well we can distinguish between frequencies. Elderly people have a diminished EEG response to binaural beats. As a effect of aging changes also take place in the envelope that follows the response. The 40 Hz response's maximum amplitude frequency decreases, the response's apparent delay lengthens, and the response's amplitude declines at modulation speeds higher than 80 Hz[68].

AEPs may be able to differentiate between the many pathophysiologies that cause central auditory processing disorder. A patient might, for instance, exhibit abnormalities in some AEP segments but not in other ones. Unless the ABR is recorded, a patient with auditory neuropathy might not be able to be distinguished from a patient with central auditory processing disorder. It could be possible to develop a battery of electrophysiological tests that can distinguish between different central auditory processing disorder causes.

The Johnson et al. speech ABR, the FFR, and the ABR should all be included in such a battery[69].

Evidence from this review has helped to demonstrate the value of using a regulated P300 methodology to identify and keep tabs on Cochlear Implant users. We observed a pattern in the rise in delay and reduction in amplitude among Cochlear Implant users, independent of the stimuli used to trigger P300. The speech test results and the participant's cumulative experience with the Cochlear Implant speech processor appear to be connected to the P300 latency and amplitude data[70].

A non-invasive objective technique called mismatch negativity (MMN) is utilised in clinical studies to evaluate cortical auditory discrimination. It relates to the instinctive recognition of a distinction between the sensory stimulus that is perceived and the sensory memory trail left by earlier stimuli. Because MMN exists, it follows that every stimulus leaves a neural record that exactly codes its physical features. The auditory memory is formed by this trace and is strengthened by stimulus recurrence[71], [72].

In subjects with normal hearing, MMN corresponds to the beginning of a negative wave 100–250 ms following the aberrant stimuli. A negative potential field connected to polar inversion in the mastoid dominates in frontocentral regions.

In individuals who have normal hearing, the producers are found in the primary auditory cortex, while a few writers have proposed an additional producer in the frontal and prefrontal cortex. Right-hemisphere dominance in speech processing in noisy environment  and left-hemisphere predominance in silence were discovered in a cortical auditory discrimination study by MMN in normal-hearing participants[73], [74].

When considered as a whole, these results imply that MMN may serve as an objective electrophysiological indicator of the cortical auditory discrimination ability in cochlear implant recipients. Thus, it might allow for an objective evaluation of speech discrimination, particularly in young cochlear implant recipients.

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| Paper | Age Group | Trials | stimulus Type of Delivery | Signal Analysed\_AEP\_EEG | Findings |
| Hearing Silences: Human Auditory Processing Relies on Preactivation of Sound-Specific Brain Activity Patterns | N=19,Age: 21 - 30,11F +8M | 1120 sound trials , | Clicks,1000hz,binaurally through headphones (70 dB HD 25-1, Sennheiser) without delay after the button press | Event-related potential analysis Topographic analysis and Source Analysis of AEP | Electrophysiological brain signals showed that when a clear prediction can be formulated, the brain activates a template of its response to the predicted stimulus before it arrives to our senses. |
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| Age-related differences in binaural masking level differences: behavioral and electrophysiological evidence | N=30 ,YNH age 19–26 yr ONH age 61–73 yr ,21F+5M | 2,200 sweeps | Tone,500hz,Binaurally at 55-dB SL through ER-1 insert earphones at a rate of 4.76 Hz and theWB and NB stimuli were presented at -10-dB SNR in a continuous loop | Spectral magnitudes were calculatedfrom each response using Fast Fourier transforms with one 20-Hz bincentered around 500 Hz over the time response region (5–100 ms). | we generally found decreased spectral magnitudes in the dichotic compared with diotic configurations, demonstrating binaural processing effects. |  |
| Cortical Correlates of Binaural Temporal Processing Deficits in Older Adults | N=30 ,10 (YNH) ages 21- 32 years ,10 (ONH) ages 61-78 years,10 (OHI) ages 61-81 years,23 F+7M | 60 | Tone,500hz ,Binaurally at 55-dB SL through ER-1 insert earphones at a rate of 4.76 Hz and theWB and NB stimuli were presented at -10-dB SNR in a continuous loop | CAEP N1-P2 peak amplitude | this study demonstrated determined that such changes can be reliably measured and indexed using either behavioral or CAEP threshold measurement techniques. |  |
| EEG activity as an objective measure of cognitive load during effortful listening: A study on pediatric subjects with bilateral, asymmetric sensorineural hearing loss | N=7, age8 -18 years, (4F +3M, | 20 | speech delivered free-field at an intensity of 65 dB HL by a loudspeaker set 1 m in front of the patient. Continuous 4-talker babble background noise was used as the competing signal in order to provide informational masking, . | EEG Power Spectral Density (PSD) in the theta band and parietal EEG PSD in the alpha band, as assessed before stimulus (word) onset. | Significantly higher parietal alpha power levels in two of three noisy conditions, compared to the quiet condition, are consistent with increased cognitive load. |  |
| Effects of Sensorineural Hearing Loss on Cortical Synchronization to Competing Speech during Selective Attention | N=44,22 HI; 22 NH;, 38F+6M | 180 tone repetitions. | 1 kHz tone pulse, 0.5-s-long 40 Hz tone sequences alternated with 0.5-s-long silence intervals, resulting in a periodic 4 Hz onset/offset pattern,. In the second paradigm, no 4 Hz onset/offset pattern was imposed | ITPC results in short time windows.The inter trial phase coherence (ITPC) was computed for EEG responses to EFR stimuli | HI listeners also exhibited a reduced temporal masking release compared with the NH listeners |  |
| Brain Stem and Cortical Mechanisms Underlying the Binaural Masking Level Difference in Humans: An Auditory Steady-State Response Study | mean age: 25.5 yr | 48 EEG sweeps | AM stimuli with 500hz carriere(when the signal and noise are in phase binaurally: SoNo) and dichotic AM stimuli (when either the signal or noise is 180° out-of-phase between the two ears: SNo,SoN) | FFT of ASSR | Results suggest that brain processes underlying the BMLD occur either in a different pathway or beyond the brain stem auditory processing underlying the 80-Hz ASSR. |  |
| Does the 40-Hz Auditory Steady-State Response Show the Binaural Masking Level Difference? | N=10 ;mean age: 27.4 yr ;6F+4M | 48 sweeps collected per condition | 500-Hz tone,thresholds were obtained for four signal-masker conditions: “So,” “SoNo,” “SNo,” and “SoN.”,100% sinusoidally amplitude-modulated at 40 h | A two-way repeated-measures analysis of variance (ANOVA) was performed to evaluate the effects of “response type” and “stimulus condition” (signal versus noise inversion) on the BMLD, | 40-Hz ASSR thresholds do not reflect the BMLD, the amplitude suppression under dichotic conditions may be a precursor to the subsequent <20-Hz ASSR and behavioral BMLDs. |  |
| Age-Related Deficits in Electrophysiological and Behavioral Measures of Binaural Temporal Processing | N=30 ; ages of 35 to 74 years (mean age: 62.3 years) ;11F+19M | 75 trails | 500-Hz tone that was 100% sinusoidally amplitude modulated (AM) ,the target stimulus contained monaural FM that was out of phase at the two ears, with modulator starting phases of 0 and π radians. | IPM-FRs were obtained as the spectral magnitude in the 6.8-Hz bin while ASSRs were obtained as the spectral magnitude in the 40.8- or 81.6-Hz bins for each participant from the electrode at the right mastoid (M2). | IPM-FR reflects age-related declines in binaural temporal processing and provide further evidence that this response may represent a useful objective tool for assessing binaural function. |  |
| Neural correlates of masked and unmasked tones:  psychoacoustics and late auditory evoked potentials  (LAEPs | N=15 9F+6M | 400 trails 3 conditions | tone 700hz stimulus consisted of five noise bands as a 131 masker and a pure tone as a target signal: one noise band was centered at the frequency of the target tone 132 (center band, CB). | Late auditory evoked potentials (LAEPs),N1-P2 | P2 amplitudes were more closely linked to behavioral measures than the N1 amplitudes. Both behavioral and electrophysiological measures suggest that the salience of a masked tone at supra-threshold levels is correlated with the amount of masking release. |  |
| Masking Level Difference and Electrophysiological Evaluation in Adults with Normal Hearing | N=20; agebetween 18 and 30 yearse, All females | 2,048 | clicks and syllable; presented monoaurally using insert earphones at 80 dBnHL, at a presentation rate of , lasting 0.1 ms, acoustic stimulus had duration of 40 ms, presented monoaurally to the right ear at 80 dBnHL,at a presentation rate of 10.9 stimuli per second. | Interpeaks I-III, III-V, IV of the BAEP,latency of the V, A, C, D, E, F and O waves of the FFR, | The mean MLD correlated with the BAEP with click stimulus and the FFR; the higher the latencies of the V, A and F waves of the FFR, the greater the MLD |  |
| Binaural Interaction Component of Middle Latency Response in Children Suspected to Central Auditory Processing Disorder | N=120 8–12 year-old 60 CAPD and 60 normal children ;80 boys and 40 girls | not mentioned | Click stimuli, 70 dBHL, 7.1/s rate, and rarefaction polarity, filter setting of 15–250 Hz. Stimuli were delivered through insert phone. Patients were awake and lied down on bed in an acoustic room. | Pa–Na latencey (lv),BIC latencey Pa–Na amplitude (lv),BIC amplitude | study showed that MLR and BIC of MLR in children with suspected (C)APD were significantly different from normal children. Therefore MLR and its’ BIC are clinically available and objective tests that can be used for determining children suspected to (C)APD |  |
| A novel stimulus paradigm for simultaneous recording of monaural and binaural frequency following response for identification of binaural interaction component | N=26 between 20 to 40 years (mean age= 25.15 years) ;19F+7M | 2,000 | Pure tones were presented sequentially in two ears with partial overlap of pure tones (50 msec). .. In ‘stimulus with gap’ condition, pure tones with a duration of 50 msec were used to elicit the FFR. | FFR:The averaged waveforms obtained from all participants were subjected to spectral analysis. Spectral analysis was | The novel stimulus presentation paradigm used in the present study could be used for obtaining monaural and binaural FFRs in the same recording for identification of BIC. |  |

**Behavioral and electrophysiological masking level difference**

Electrophysiological test for binaural hearing loss has better accuracy as compared to behavioral test because they don’t depend on an individual's subjective reaction.

Electrophysiological approaches to calculating the BMLD should be researched as an alternate method for patients who cannot do behavioral tasks.

Continuous change Frameworks have been used to show that the BMLD could be computed from auditory cortical responses in subjects with normal hearing to investigate physiological implications of the BMLD in humans[26], [75].

AEPs were analyzed to develop the correlation between behavioral BMLD and the neurological response of the binaural hearing pathway.

AEPs are identified by the latency with which they arise measured in milliseconds. First Response which occurs between 0 and 10 milliseconds after stimuli are known as auditory brain response is presented. Middle latency response(MLR) appears between 10 to 100 ms and other AEPs that occurs after 100ms are late latency response(LLR), Cortical Auditory-Evoked Potentials (CAEP), and the Mismatch Negativity (MMN) response[76].

MLR was measured using a BMLD Test and a reduction in amplitudes was observed with a change in IPDs[77].

BMLD comes from the SOC, and the amplitude of ABR wave III should correlate with the size of behavioral BMLD, it was shown Multiple sclerosis patients reported reduced MLDs and ABR wave III amplitudes[78].

P1-N1-P2-N2 AEP in a BMLD paradigm with 15 dB and 500 Hz tone burst stimuli is correlated to behavioral BMLD[75].

A similar BMLD paradigm was applied to older subjects, and after analyzing CEAP, it was found that an age-related drop in CAEP is compatible with behavioral BMLDs[79].

Frequency-Following Response (FFR) is a neural response that is synced to auditory stimuli and pure tones, synthetic speech sounds, spontaneously produced vowels, and tonal sweeps are some examples of stimuli that might elicit it. In a study to establish the relationship between behavioral BMLD and FFR unmasking, a larger FFR SNR in antiphasic conditions was observed compared to FFR SNR in homophasic conditions[60].

Auditory steady-state responses (ASSRs) is an AEPs which is elicited with the modulated tone as a stimulus.

It was established that Cortical ASSR evoked with a modulation frequency of 7 Hz or 13 Hz has higher BMLD[80].

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| Author | Date | behavioral measure | Objective measure | finding |
| While Jerger | 1982 | BMLD | FFR | Subjects with a delayed latency or no wave III were linked to lower BMLDs |
| Mikami | 1992 | BMLD | LEAP | LAEP characteristics are similar to but not identical to behavioral MLD. |
| C G Fowler | 1996 | BMLD | MLR | failed to demonstrate MLD-like characteristics in the middle latency potentials |
| C G Fowler | 1996 | BMLD | LLR | similarity in P2 and BMLD was found |
| Wong and Stapells | 2004 | BMLD | ASSR | The ASSR BMLDs were much lower than the behavioral BMLDs' elicited responses. |
| Wilson and Krishnan | 2005 | BMLD | FFR | larger FFR signal-to-noise ratios in antiphasic conditions relative to FFR signal-to-noise ratios in homophasic conditions, consistent with unmasking |
| Ieda Maria Ishida | 2009 | BMLD | 40hz ASSR | 40-Hz ASSR thresholds do not reflect the BMLD |
| Christopher G. Clinard | 2017 | BMLD | FFR | Differences in FFR amplitude is effective predictor of behavioral BMLDs. |
| Charlotte Vercammen | 2018 | IPD thresholds | IPM-FRs | the behavioral IPD discrimination thresholds and the dynamic range of the IPM-FR were still significantly correlated |
| David A. Eddins | 2018 | BMLD | CAEP | For diotic stimuli, behavioral and CAEP thresholds were highly correlated |
| Z Lagidze | 2020 | FM thresholds | IPM-FRs | IPM-FR was predictive of performance on the binaural frequency modulation detection task |
| Z Kevanishvili | 2020 | BMLD | IPM-FRs | IPM-FR was not predictive of the spatial release-from-masking task |
| Tobias Balkenhol | 2020 | Audiometry | P2 latencies | P2 latencies between mono and bimodal condition of the CI users showed significant correlations. |

**REFERENCES**

[1] F. R. Lin, R. Thorpe, S. Gordon-Salant, and L. Ferrucci, “Hearing loss prevalence and risk factors among older adults in the United States,” *J. Gerontol. Ser. Biomed. Sci. Med. Sci.*, vol. 66, no. 5, pp. 582–590, 2011.

[2] World Health Organization, *World report on hearing: executive summary*. World Health Organization, 2021. Accessed: Sep. 25, 2022. [Online]. Available: https://apps.who.int/iris/handle/10665/339956

[3] “Ear and hearing health of Aboriginal and Torres Strait Islander people 2021, Summary,” *Australian Institute of Health and Welfare*. https://www.aihw.gov.au/reports/indigenous-australians/ear-and-hearing-health-of-aboriginal-torres-strait/summary (accessed Sep. 25, 2022).

[4] L. J. Dickinson, M. Nimmo, R. P. Morton, and S. C. Purdy, “‘Asymptomatic’South Auckland preschool children have significant hearing loss and middle ear disease,” *Int. J. Pediatr. Otorhinolaryngol.*, vol. 114, pp. 106–110, 2018.

[5] L. M. Haile *et al.*, “Hearing loss prevalence and years lived with disability, 1990–2019: findings from the Global Burden of Disease Study 2019,” *The Lancet*, vol. 397, no. 10278, pp. 996–1009, 2021.

[6] P. Avan, F. Giraudet, and B. Büki, “Importance of binaural hearing,” *Audiol. Neurotol.*, vol. 20, no. Suppl. 1, pp. 3–6, 2015.

[7] F. J. Gallun, “Impaired Binaural Hearing in Adults: A Selected Review of the Literature,” *Front. Neurosci.*, vol. 15, 2021, Accessed: Sep. 06, 2022. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnins.2021.610957

[8] J. Venturi, “Considérations sur la connaissance de l’étendue que nous donne le sens de l’ouïe,” *Mag. Encycl. Ou J. Sci. Lett. Arts*, vol. 3, pp. 29–37, 1796.

[9] Lord Rayleigh, “XII. On our perception of sound direction,” *Lond. Edinb. Dublin Philos. Mag. J. Sci.*, vol. 13, no. 74, pp. 214–232, 1907.

[10] B. G. Shinn-Cunningham, S. Santarelli, and N. Kopco, “Tori of confusion: Binaural localization cues for sources within reach of a listener,” *J. Acoust. Soc. Am.*, vol. 107, no. 3, pp. 1627–1636, 2000.

[11] S. S. Stevens and E. B. Newman, “The localization of actual sources of sound,” *Am. J. Psychol.*, vol. 48, pp. 297–306, 1936, doi: 10.2307/1415748.

[12] A. W. Mills, “On the Minimum Audible Angle,” *J. Acoust. Soc. Am.*, vol. 30, no. 4, pp. 237–246, Apr. 1958, doi: 10.1121/1.1909553.

[13] E. G. WALSH, “An investigation of sound localization in patients with neurological abnormalities,” *Brain*, vol. 80, no. 2, pp. 222–250, 1957.

[14] G. C. Stecker and F. Gallun, “Binaural Hearing, Sound Localization, and Spatial Hearing,” 2012.

[15] C. E. Carr and M. Konishi, “A circuit for detection of interaural time differences in the brain stem of the barn owl,” *J. Neurosci.*, vol. 10, no. 10, pp. 3227–3246, Oct. 1990, doi: 10.1523/JNEUROSCI.10-10-03227.1990.

[16] “Directional Hearing Capacity in Hearing Disorders: Acta Oto-Laryngologica: Vol 48, No 5-6.” https://www.tandfonline.com/doi/abs/10.3109/00016485709126908 (accessed Sep. 12, 2022).

[17] R. Häusler, S. Colburn, and E. Marr, “Sound localization in subjects with impaired hearing. Spatial-discrimination and interaural-discrimination tests,” *Acta Oto-Laryngol. Suppl.*, vol. 400, pp. 1–62, 1983, doi: 10.3109/00016488309105590.

[18] I. J. Hirsh, “Binaural summation and interaural inhibition as a function of the level of masking noise,” *Am. J. Psychol.*, vol. 61, pp. 205–213, 1948, doi: 10.2307/1416966.

[19] “The Influence of Interaural Phase Relations upon the Masking of Speech by White Noise: The Journal of the Acoustical Society of America: Vol 20, No 2.” https://asa.scitation.org/doi/abs/10.1121/1.1906358 (accessed Sep. 12, 2022).

[20] D. McFadden, “Masking-level differences determined with and without interaural disparities in masker intensity,” *J. Acoust. Soc. Am.*, vol. 44, no. 1, pp. 212–223, Jul. 1968, doi: 10.1121/1.1911057.

[21] N. Marrone, C. R. Mason, and G. Kidd, “The effects of hearing loss and age on the benefit of spatial separation between multiple talkers in reverberant rooms,” *J. Acoust. Soc. Am.*, vol. 124, no. 5, pp. 3064–3075, Nov. 2008, doi: 10.1121/1.2980441.

[22] J. Peissig and B. Kollmeier, “Directivity of binaural noise reduction in spatial multiple noise-source arrangements for normal and impaired listeners,” *J. Acoust. Soc. Am.*, vol. 101, no. 3, pp. 1660–1670, Mar. 1997, doi: 10.1121/1.418150.

[23] T. L. Arbogast, C. R. Mason, and G. Kidd, “The effect of spatial separation on informational masking of speech in normal-hearing and hearing-impaired listeners,” *J. Acoust. Soc. Am.*, vol. 117, no. 4 Pt 1, pp. 2169–2180, Apr. 2005, doi: 10.1121/1.1861598.

[24] C. Witton, G. G. Green, A. Rees, and G. B. Henning, “Monaural and binaural detection of sinusoidal phase modulation of a 500-Hz tone,” *J. Acoust. Soc. Am.*, vol. 108, no. 4, pp. 1826–1833, 2000.

[25] J. H. Grose and S. K. Mamo, “Frequency modulation detection as a measure of temporal processing: Age-related monaural and binaural effects,” *Hear. Res.*, vol. 294, no. 1–2, pp. 49–54, 2012.

[26] C. G. Fowler and C. M. Mikami, “The late auditory evoked potential masking-level difference as a function of noise level,” *J. Speech Lang. Hear. Res.*, vol. 35, no. 1, pp. 216–221, 1992.

[27] B. Ross, T. Fujioka, K. L. Tremblay, and T. W. Picton, “Aging in binaural hearing begins in mid-life: evidence from cortical auditory-evoked responses to changes in interaural phase,” *J. Neurosci.*, vol. 27, no. 42, pp. 11172–11178, 2007.

[28] S. Anderson, R. Ellis, J. Mehta, and M. J. Goupell, “Age-related differences in binaural masking level differences: behavioral and electrophysiological evidence,” *J. Neurophysiol.*, vol. 120, no. 6, pp. 2939–2952, Dec. 2018, doi: 10.1152/jn.00255.2018.

[29] T. K. Koerner, R. K. Muralimanohar, F. J. Gallun, and C. J. Billings, “Age-Related Deficits in Electrophysiological and Behavioral Measures of Binaural Temporal Processing,” *Front. Neurosci.*, vol. 14, 2020, Accessed: Sep. 12, 2022. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnins.2020.578566

[30] F. A. Webster, “The Influence of Interaural Phase on Masked Thresholds I. The Role of Interaural Time‐Deviation,” *J. Acoust. Soc. Am.*, vol. 23, no. 4, pp. 452–462, Jul. 1951, doi: 10.1121/1.1906787.

[31] “Effect of Peripheral Hearing Loss on the Masking Level Difference | JAMA Otolaryngology–Head & Neck Surgery | JAMA Network.” https://jamanetwork.com/journals/jamaotolaryngology/article-abstract/611438 (accessed Sep. 18, 2022).

[32] J. G. Staffel, J. W. Hall, J. H. Grose, and H. C. Pillsbury, “NoSo and NoSπ detection as a function of masker bandwidth in normal‐hearing and cochlear‐impaired listeners,” *J. Acoust. Soc. Am.*, vol. 87, no. 4, pp. 1720–1727, Apr. 1990, doi: 10.1121/1.399420.

[33] D. McFadden, “Masking‐Level Differences with Continuous and with Burst Masking Noise,” *J. Acoust. Soc. Am.*, vol. 40, no. 6, pp. 1414–1419, Dec. 1966, doi: 10.1121/1.1910241.

[34] B. C. J. Moore and D. A. Vickers, “The role of spread excitation and suppression in simultaneous masking,” *J. Acoust. Soc. Am.*, vol. 102, no. 4, pp. 2284–2290, Oct. 1997, doi: 10.1121/1.419638.

[35] H. S. Colburn and N. I. Durlach, “Models of binaural interaction,” *Handb. Percept.*, vol. 4, pp. 467–518, 1978.

[36] T. L. Langford and L. A. Jeffress, “Effect of noise crosscorrelation on binaural signal detection,” *J. Acoust. Soc. Am.*, vol. 36, pp. 1455–1458, 1964, doi: 10.1121/1.1919224.

[37] L. J. Hood, “Physiology of Binaural Hearing,” *Semin. Hear.*, vol. 18, no. 4, pp. 313–320, Nov. 1997, doi: 10.1055/s-0028-1083034.

[38] J. W. Hall and A. D. G. Harvey, “Diotic Loudness Summation in Normal and Impaired Hearing,” *J. Speech Lang. Hear. Res.*, vol. 28, no. 3, pp. 445–448, Sep. 1985, doi: 10.1044/jshr.2803.448.

[39] J. H. Grose, J. W. Hall, and M. B. Dev, “MLD in Children,” *J. Speech Lang. Hear. Res.*, vol. 40, no. 4, pp. 955–959, Aug. 1997, doi: 10.1044/jslhr.4004.955.

[40] J. W. Hall, R. S. Tyler, and M. A. Fernandes, “Monaural and binaural auditory frequency resolution measured using bandlimited noise and notched‐noise masking,” *J. Acoust. Soc. Am.*, vol. 73, no. 3, pp. 894–898, 1983.

[41] D. A. Eddins and L. E. Barber, “The influence of stimulus envelope and fine structure on the binaural masking level difference,” *J. Acoust. Soc. Am.*, vol. 103, no. 5, pp. 2578–2589, May 1998, doi: 10.1121/1.423112.

[42] J. W. Hall III, J. H. Grose, and W. M. Hartmann, “The masking-level difference in low-noise noise,” *J. Acoust. Soc. Am.*, vol. 103, no. 5, pp. 2573–2577, 1998.

[43] W. A. Yost and R. H. Dye, “Discrimination of interaural differences of level as a function of frequency,” *J. Acoust. Soc. Am.*, vol. 83, no. 5, pp. 1846–1851, May 1988, doi: 10.1121/1.396520.

[44] J. D. Durrant, R. J. Nozza, R. J. Hyre, and D. L. Sabo, “Masking level difference at relatively high masker levels: preliminary report,” *Audiol. Off. Organ Int. Soc. Audiol.*, vol. 28, no. 4, pp. 221–229, 1989, doi: 10.3109/00206098909081627.

[45] L. R. Bernstein, S. van de Par, and C. Trahiotis, “The normalized interaural correlation: Accounting for NoSπ thresholds obtained with Gaussian and ‘low-noise’ masking noise,” *J. Acoust. Soc. Am.*, vol. 106, no. 2, pp. 870–876, Aug. 1999, doi: 10.1121/1.428051.

[46] A. Kohlrausch, “The influence of signal duration, signal frequency and masker duration on binaural masking level differences,” *Hear. Res.*, vol. 23, no. 3, pp. 267–273, 1986, doi: 10.1016/0378-5955(86)90115-2.

[47] “Assessment of auditory discrimination in hearing-impaired patients | Elsevier Enhanced Reader.” https://reader.elsevier.com/reader/sd/pii/S1879729618300607?token=36B6F9BED5EF30508F55ABA6EB5C6C4024B0C536A112657AC423C9E1A76A89043D0D58FB2BBC5B147BC88EF9C9DBBCEB&originRegion=eu-west-1&originCreation=20221024202241 (accessed Oct. 25, 2022).

[48] A. P. Bradley and W. J. Wilson, “Automated analysis of the auditory brainstem response,” presented at the Proceedings of the 2004 Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004., 2004, pp. 541–545.

[49] M. Rushaidin, S.-H. Salleh, T. T. Swee, J. Najeb, and A. Arooj, “Wave V detection using instantaneous energy of auditory brainstem response signal,” *Am. J. Appl. Sci.*, vol. 6, no. 9, p. 1669, 2009.

[50] M. P. Paulraj, K. Subramaniam, S. B. Yaccob, A. H. B. Adom, and C. R. Hema, “Auditory Evoked Potential Response and Hearing Loss: A Review,” *Open Biomed. Eng. J.*, vol. 9, pp. 17–24, Feb. 2015, doi: 10.2174/1874120701509010017.

[51] W. Woodworth, S. Reisman, and A. B. Fontaine, “The Detection of Auditory Evoked Responses Using a Matched Filter,” *IEEE Trans. Biomed. Eng.*, vol. BME-30, no. 7, pp. 369–376, Jul. 1983, doi: 10.1109/TBME.1983.325036.

[52] J. Tian, M. Juhola, and T. Grönfors, “Latency estimation of auditory brainstem response by neural networks,” *Artif. Intell. Med.*, vol. 10, no. 2, pp. 115–128, Jun. 1997, doi: 10.1016/S0933-3657(97)00389-8.

[53] D. Alpsan and O. Ozdamar, “Brainstem auditory evoked potential classification by backpropagation networks,” presented at the [Proceedings] 1991 IEEE International Joint Conference on Neural Networks, 1991, pp. 1266–1271.

[54] J. A. G. Gnecchi, L. R. S. Lara, and J. C. H. Garcia, “Design and construction of an EEG data acquisition system for measurement of auditory evoked potentials,” presented at the 2008 Electronics, Robotics and Automotive Mechanics Conference (CERMA’08), 2008, pp. 547–552.

[55] O. Ozdamar, J. Bohorquez, T. Mihajloski, E. Yavuz, and M. Lachowska, “Auditory evoked responses to binaural beat illusion: stimulus generation and the derivation of the Binaural Interaction Component (BIC),” presented at the 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2011, pp. 830–833.

[56] T. Picton, “Hearing in Time: Evoked Potential Studies of Temporal Processing,” *Ear Hear.*, vol. 34, no. 4, pp. 385–401, Jul. 2013, doi: 10.1097/AUD.0b013e31827ada02.

[57] R. Snyder and C. Schreiner, “The auditory neurophonic: basic properties,” *Hear. Res.*, vol. 15, no. 3, pp. 261–280, 1984.

[58] F. H. Veld, P. Osterhammel, and K. Terkildsen, “Frequency following auditory brain stem responses in man,” *Scand. Audiol.*, vol. 6, no. 1, pp. 27–34, 1977.

[59] A. Krishnan, “Human frequency following response,” *Audit. Evoked Potentials Basic Princ. Clin. Appl.*, pp. 313–335, 2007.

[60] J. R. Wilson and A. Krishnan, “Human Frequency-Following Responses to Binaural Masking Level Difference Stimuli,” *J. Am. Acad. Audiol.*, vol. 16, no. 3, pp. 184–195, Mar. 2005, doi: 10.3766/jaaa.16.3.6.

[61] H. E. Gockel, R. P. Carlyon, A. Mehta, and C. J. Plack, “The frequency following response (FFR) may reflect pitch-bearing information but is not a direct representation of pitch,” *J. Assoc. Res. Otolaryngol.*, vol. 12, no. 6, pp. 767–782, 2011.

[62] Ra. Dobie and S. Norton, “Binaural interaction in human auditory evoked potentials,” *Electroencephalogr. Clin. Neurophysiol.*, vol. 49, no. 3–4, pp. 303–313, 1980.

[63] B. Ross, S. A. Hillyard, and T. W. Picton, “Temporal dynamics of selective attention during dichotic listening,” *Cereb. Cortex*, vol. 20, no. 6, pp. 1360–1371, 2010.

[64] D. W. Purcell, S. M. John, B. A. Schneider, and T. W. Picton, “Human temporal auditory acuity as assessed by envelope following responses,” *J. Acoust. Soc. Am.*, vol. 116, no. 6, pp. 3581–3593, 2004.

[65] X. Tan, Q. Fu, H. Yuan, L. Ding, and T. Wang, “Improved transient response estimations in predicting 40 Hz auditory steady-state response using deconvolution methods,” *Front. Neurosci.*, vol. 11, p. 697, 2017.

[66] B. Ross, B. Schneider, J. S. Snyder, and C. Alain, “Biological markers of auditory gap detection in young, middle-aged, and older adults,” *PLoS One*, vol. 5, no. 4, p. e10101, 2010.

[67] Y. Mandel *et al.*, “Cortical responses elicited by photovoltaic subretinal prostheses exhibit similarities to visually evoked potentials,” *Nat. Commun.*, vol. 4, no. 1, pp. 1–9, 2013.

[68] C. G. Clinard, K. L. Tremblay, and A. R. Krishnan, “Aging alters the perception and physiological representation of frequency: evidence from human frequency-following response recordings,” *Hear. Res.*, vol. 264, no. 1–2, pp. 48–55, 2010.

[69] M. Basu, A. Krishnan, and C. Weber‐Fox, “Brainstem correlates of temporal auditory processing in children with specific language impairment,” *Dev. Sci.*, vol. 13, no. 1, pp. 77–91, 2010.

[70] M. S. A. do Amaral *et al.*, “The P300 Auditory Evoked Potential in Cochlear Implant Users: A Scoping Review,” *Int. Arch. Otorhinolaryngol.*, Jul. 2022, doi: 10.1055/s-0042-1744172.

[71] C. C. Duncan *et al.*, “Event-related potentials in clinical research: Guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400,” *Clin. Neurophysiol.*, vol. 120, no. 11, pp. 1883–1908, Nov. 2009, doi: 10.1016/j.clinph.2009.07.045.

[72] M. J. Taylor and T. Baldeweg, “Application of EEG, ERP and intracranial recordings to the investigation of cognitive functions in children,” *Dev. Sci.*, vol. 5, no. 3, pp. 318–334, 2002.

[73] M. Giard, F. Perrin, J. Pernier, and P. Bouchet, “Brain generators implicated in the processing of auditory stimulus deviance: a topographic event‐related potential study,” *Psychophysiology*, vol. 27, no. 6, pp. 627–640, 1990.

[74] M. Gomot, M.-H. Giard, S. Roux, C. Barthélémy, and N. Bruneau, “Maturation of frontal and temporal components of mismatch negativity (MMN) in children,” *Neuroreport*, vol. 11, no. 14, pp. 3109–3112, 2000.

[75] C. G. Fowler and C. M. Mikami, “Effects of noise bandwidth on the late-potential masking level difference,” *Electroencephalogr. Clin. Neurophysiol. Potentials Sect.*, vol. 84, no. 2, pp. 157–163, Mar. 1992, doi: 10.1016/0168-5597(92)90020-C.

[76] “Head Size as a Basis of Gender Difference in the Latency of the Brainstem Auditory-Evoked Response: Audiology: Vol 29, No 2.” https://www.tandfonline.com/doi/abs/10.3109/00206099009081652 (accessed Sep. 17, 2022).

[77] C. G. Fowler and C. Mikami, “Phase effects on the middle and late auditory evoked potentials,” *J.-Am. Acad. Audiol.*, vol. 7, pp. 23–30, 1996.

[78] D. Noffsinger, C. Martinez, and A. Schaefer, “Auditory brainstem responses and masking level differences from persons with brainstem lesion.,” *Scand. Audiol. Suppl.*, vol. 15, pp. 81–93, 1982.

[79] A. C. Eddins, E. J. Ozmeral, and D. A. Eddins, “How aging impacts the encoding of binaural cues and the perception of auditory space,” *Hear. Res.*, vol. 369, pp. 79–89, 2018.

[80] W. Y. S. Wong and D. R. Stapells, “Brain Stem and Cortical Mechanisms Underlying the Binaural Masking Level Difference in Humans: An Auditory Steady-State Response Study.”