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REVIEW ARTICLE

Spatial auditory processing in children with central auditory processing disorder

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Abstract

Background and Aim: Spatial hearing is one of the most important functions of binaural hearing processing that is based on detection of fine interaural time and interaural intensity difference. Spatial hearing is beyond auditory localization and lateralization. It helps auditory scene analysis and target stream segregation from other simultaneous sound sources. This function is important in speech perception in presence of competing messages. The aim of the present paper was reviewing spatial hearing, plasticity of binaural hearing in auditory system and spatial hearing disorder in children with central auditory processing disorder ((C)APD).

Recent Findings: Recent studies show that spatial hearing disorder is one of the important problems in relatively high proportion of children with (C)APD. It is proposed that spatial processing disorder can cause speech perception difficulty in noise which is the main complaint of children with (C)APD. Spatial hearing rehabilitation through sound localization and lateralization training can be effective in improvement of speech perception in noise.

Conclusion: In children suspected to (C)APD, spatial hearing evaluation is vital. Spatial hearing can be evaluated by using sound localization and lateralization tests. If spatial hearing disorder is detected, special rehabilitation is necessary to address this central processing problem. This rehabilitation has a potential to improve speech perception in noise.

Keywords: Central auditory processing; spatial hearing; speech perception in noise; sound localization; pediatrics

Introduction

The auditory processing and its disorder were introduced at 1950, and a technical report about central auditory processing disorder ((C)APD) was published by ASHA at 1995. Afterwards a series of test batteries (behavioral, physiological and electrophysiological tests) have been reported for detecting the subjects with (C)APD [1].

Auditory processing includes all processes that determine sound source direction and type (identity and content), separate stimulus from background noise and lead to stimulus interpretation. Sound goes under a variety of processing in the central nuclei of auditory system and because of this processing, binaural information is compared, auditory patterns are extracted and frequency and amplitude modulations are detected [2].

Auditory system is able to represent temporal changes in acoustic signals and can process the transient acoustic events. Appropriate auditory perception needs temporal resolution processing in scale of microseconds (μs) for binaural cues,

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milliseconds (ms) for detection of neural synchronization, tens of seconds for the transient speech processing, and hundreds of ms for processing of speech prosody and supra segmental properties. Moreover the auditory system has to be sensitive towards the order of sound events and must be able to integrate the auditory information in time. The important acoustic cues in stimulus (e.g. stimulus onset) are improved in brainstem and auditory efferent pathway shapes the processing of lower auditory stations. The outcome of this processing reaches to the auditory cortex to eventually stimuli can be differentiated and identified. These processes enable auditory system to identify fine differences between stimuli (frequency, duration and minimal pairs). All these processes lead to auditory behaviors such as sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal integration, temporal order, auditory function in the presence of competing signal and auditory function with degraded sounds. (C)APD includes impairment of one or more auditory behavior(s) that may occur because of one or more central auditory processing disorder(s) [2].

Children with (C)APD are a heterogeneous group and all the children with (C)APD do not have the same symptoms, but they generally have normal IQ and hearing threshold level [3]. They mainly have weak listening performance in noisy environments [4]. It is reported that they have problems in auditory skills, learning difficulty through hearing modality, auditory short term memory disorder, and difficulty in understanding the message in noisy environments. They frequently ask others to repeat their message or misinterpret their message. They also show weak auditory attention, delayed and slow response to verbal stimuli, difficulty to separate message from background noise, and difficulty in perception of quick message, and academic difficulty [5].

(C)APD may occur alone or companied with developmental or neurologic disorders. Therefore, (C)APD is different from linguistic, cognitive or attention disorders [3]. According to British Society of Audiology (BSA) there are three types of (C)APD, a) developmental which exists from early childhood, b) acquired occurs after head trauma or infection, and c) secondary which occurs after hearing loss [6].

Diagnostic evaluation of (C)APD

Most of the children with (C)APD, process the speech in a normal way in desired listening conditions. The distorted/degraded speech, and speech in presence of noise or competing speech tests are useful to diagnose this disorder. Some children who have poor performance in (C)APD tests, show speech or language difficulties but others have no speech or language problems. Some times (C)APD tests cannot differentiate attention problems from language deficits [3].

In general as other disorders in children can have similar behavioral manifestation as (C)APD, it can be stated that this disorder is difficult to be diagnosed. The children’s performance in (C)APD tests is affected by some non-auditory factors such as language, memory, motivation, lack of sustained attention and lack of cooperation. Early symptoms include delayed language development, phonological disorder and reading disorder, learning difficulty through auditory modality, limited capacity of auditory memory and weak memory of the auditory sequence. It is very important that (C)APD can be diagnosed in early age for suitable treatment occurs before educational failure [7].

Minimum test battery for determining (C)APD is audiometry, acoustic immittance test, word recognition score, dichotic hearing, duration pattern recognition, otoacoustic emissions (OAE), auditory brainstem response (ABR), and middle latency response (MLR). Chermak and Musiek suggested several tests for (C)APD diagnosis at the first steps such as dichotic digits, competing sentence, frequency pattern, pediatric speech identification (PSI), and then they introduced staggered spondiac word (SSW), MLR, Tallal’s tests, compressed speech for second step. Ferre and Bellis mentioned the minimum tests for evaluating (C)APD are as follow: the speech dichotic tasks, monaural low redundancy tasks, temporal pattern and binaural interaction tasks. Different sets of tests for (C)APD

Table 1. Central auditory processing domains and related tests in multiple auditory processing assessment (MAPA)

Central auditory processing domain	tests
1- Monaural with low redundancy	mSAAT
2- Temporal	Tap test, PPST
3- Dichotic	DDT, CST

mSAAT; monaural selective auditory attention test, PPST; pitch pattern sequence test, DDT; dichotic digit test, CST; competing sentences test

diagnosis have been reported since then [1].

Finally, Domitz and Schow reported a test battery for (C)APD evaluation known as multiple auditory processing assessment (MAPA) [8] and then Show et al. published a detailed modified manual for multiple auditory processing assessment. MAPA test battery includes the following subtests, which are applicable to children at age of 8 and older (Table 1) [9].

The physiologic and neurophysiological bases of processing binaural cues in auditory system

Human beings have high sensitivity to interaural loudness difference (ILD) and interaural time difference (ITD) and they can detect even one degree deviation in angle of sound source from the head centerline. Near to head centerline, the highest spatial acuity is seen, and based on tone frequency sensitivity to ILD is almost 0.5-0.8 dB or to ITD is about 10-15ms [3].

The anatomical bases of sound source detection are the neurons with binaural inputs and they are sensitive to the phase difference or sound stimulus intensity. The first ascending nuclei where right and left ear afferent neurons converge on single neurons are medial superior olivary complex (MSO) and lateral superior olivary complex (LSO) [3]. Besides sensitivity to phase difference of sound stimulus, the inferior colliculus (IC) are sensitive to dynamic changes in ITD and sound source movement as well. This characteristic is missing in MSO [10].

The auditory cortex also plays an important role in differentiating ILDs and ITDs, but it is absolutely essential for ITD discrimination as patient with bilateral damage of auditory cortex are unable to detect ITDs [11]. The cognitive localization is performed in cerebral cortex. Damage to especial areas of cortex including posterior auditory field (PAF), dorsal zone (DZ) and anterior ectosylvian sulcus (AES) in cats could affect sound source localization [12].

Unlike the visual system, auditory system receives sounds from all directions. This omnidirectional function and ability of localization of occluded objects are valuable for animals to survive and escape from enemy and for human beings to follow speech [13]. The spatial hearing processing is important in attention reorientation or attention switching and helps in selecting a special sound source from other back ground sound sources with various spatial directions [14].

Sound localization/lateralization test and the rehabilitation effects in human beings

The most important localization cues are ILD and ITD that depend on several factors such as head size, ear shape and the distance between two ears and they differ for every person, and they change during development specially by changing the head dimensions and two ears distance. This kind of plasticity is called developmental plasticity that acts very strongly. After developmental plasticity, spatial hearing plasticity remains partially throughout life. It is not obvious which factors cause maintenance of spatial plasticity up to adulthood. It is known that developed auditory system can adapt itself to wrong spatial cues and this is done by reweighting of spatial cues [15] and localization training program is able to improve localization [16]. Sound localization is an estimation of the actual location of an auditory object in the space and is always accompanied with some inherent uncertainty and executive bias. Thus there are some errors in sound localization. The type and extent of the errors depend on the sound characteristics (such as the stimulus type e.g. tone, noise, words or sentences), environment properties, demanding task and listeners' capabilities. In fact spatial hearing provides information about acoustic environment, its physical and geometrical specifications and the location of sound source (based on emitting sounds from source). In other words, spatial hearing perception includes perception of space (its volume and shape) and location of the sound sources inside that space (identification of the primary and secondary sound sources (sound reflections) and the sound source distance from listener) [17].

Lateralization is a particular form of localization for phantom sound sources inside listener's head [18]. Depending on task, there are two types of spatial localization/lateralization judgment: a) relative or discrimination of simultaneous or sequential locations, and b) absolute localization or sound source identification that is more difficult and performs in two ways. One method for absolute localization, is direct pointing to the location of random sound source and the other is categorical localization, in which sound source location is predetermined by image around the listener and the listener must select sound source location from the limited choices [17].

The localization errors (LE) are measured in sound localization test, and these errors are indicative of two types of errors: errors of sensory processing of localization cues and errors of the method of pointing to the sound location. In categorical localization instead of angle deviation from actual sound source, the correct response is reported [19]. The purpose of the relative localization or minimum audible angle (MAA) is finding the minimum detectable difference between the angles of two similar but asynchronous sound source. The listener must mention whether the sound source is on the left or the right side of the first source [18].

The MAA for wide band stimuli is 1 to 2 degrees for front sources and for 90 degrees angle it's about 8 to 9 degrees [20]. For rear sources, MAA reaches to 6 to 7 degrees [18]. Accuracy of localization is weaker in absolute localization tasks. Absolute localization errors for wide band stimuli for front localization are 5 degrees and for lateral positions are 20 degrees [21]. It seems that absolute and relative localization tasks reflect two different abilities of human beings [22]. This view is supported by animal studies because absolute localization accuracy is affected by some brain damages that have no effects on MAA [23]. In another study Spitzer et al. observed that MAA acuity of an owl is different in reverberant and non-reverberant environment but absolute localization accuracy is similar [24,25]. These differences may be due to difference in cognitive tasks and more complexity of absolute localization [17].

Sound localization is highly plastic and may change by rehabilitation and training. Carlile et al. used short noise bursts in a free field for localization training and subjects pointed to the sound source by turning their nose toward perceived location. With training all of them showed improved auditory localization [19]. Hofman et al. indicated that the brain must learn localization cues and calibrate them based on feedback from other sensorimotor systems. They also mentioned that studies on human beings are not sufficient. They put an earplug in one of the listeners' ear and showed that their sound localization ability decreased significantly, but by time this ability improved again. Interestingly, learning new localization cues did not interfere with neural representation of primary cues because the ear with no ear plug could localize the sound as usual [26].

Wright and Fitzgerald measured discrimination threshold of ILD and ITD before and after localization training. The trainings were performed one hour per day and for nine days. After training listeners showed better ILD and ITD discrimination. At first the improvement was quick and showed generalization that is indicative of procedural learning or perceptual learning. Then it went on slower and it continued only for ILD discrimination ability and it was seen only at training frequency (no generalization) that is indicative of basic changes in stimulus process [27].

Kumpik et al. stated that during development, spatial hearing plasticity is outstanding but in adulthood, it exists only in special conditions. They showed that after occluding one ear spatial cues change, but humans can relearn horizontal localization of wide band stimuli with flat spectrum. In this investigation, subjects who received localization training on daily basis could determine the sound source location like normal ones after one week [28].

Irving and Moore, mentioned that there is little information about localization learning in the free field. They utilized wide band noise burst in 24 horizontal locations with equal distances in 360 degree. At first they used localization training (four sessions) to improve localization of all subjects. After that they occluded one ear of the subjects (by earplug) and they observed significant decrement in localization ability. Immediately after removing the earplug, their localization ability returned to the level that they had shown before ear occlusion. The result of this research showed that training could improve sound localization ability in normal hearing subjects and in subjects with unilateral conductive hearing loss (CHL). It seems that learning occurs due to reweighting, gradual changes in localization cues and development of new spatial map. Returning to the primary level of localization function after removing the earplug indicates that the original and primary localization map is retained even though new localization map is developed [29].

Firszt et al. studied the sound localization on unilateral CHL. They mentioned that these subjects have localization difficulty in challenging conditions. They performed five sessions of auditory localization training in 11 subjects with severe to profound unilateral hearing loss. Their auditory localization was evaluated with monosyllabic words and sounds with random spectral and temporal characteristics. The average localization errors after training showed that they had a considerable improvement at least in one spatial location. Subjects who had the weakest performance before the training, showed the most improvement. This research indicated that localization training should be included in rehabilitation protocol for people with severe to profound unilateral hearing loss [30].

Maturation of sound source localization ability

Functioning of the human beings' ear reach maturation soon after birth, but the central auditory nervous system (CANS) continues to grow at least in the first decade of life. Hearing experience has considerable effects on CANS throughout life. The studies of the sound localization and spatial hearing shows hearing system has a high plasticity with modification of environmental cues and this plasticity remains even in adulthood. Environmental effects may be adverse (e.g. CHL) or useful (e.g. auditory training) [15].

The neurons throughout the auditory nervous system soon after cochlea starts to function respond to single tones, therefore neural function capacity may be created before cochlear function [31]. However the more difficult auditory tasks such as localization may remain immature for years [32]. The cognitive effects (e.g. attention) may develop in parallel to auditory sense and in CANS development researches, cognitive factors should be controlled, otherwise lack of cognitive development may be mistaken for CANS under development [31].

Some of the studies show that the sound source localization matures in preschool age in normal hearing children. Of course in more complex conditions such as fused sound image movement, localization maturation occurs later [33].

The effect of binaural and spatial hearing on speech perception in noise

The head shadow effect (acoustical phenomenon) is the strongest binaural hearing advantage that can improve the signal to noise ratio (SNR) between 3 to 11 dB. The second advantage of binaural hearing is spatial hearing that can improve speech perception in noise about 16% (due to SNR improvement). The other hearing effect is squelch effect (neural phenomenon and processing) which improves SNR up to 2 dB in subjects with bilateral cochlear implant and it causes masking release [34].

Tyler et al. introduced a new method for speech in noise training by considering the spatial characteristics. They mentioned that the spatial hearing in auditory training is overlooked in present methods of auditory training, and this is an important limitation. Binaural hearing training has many benefits. Most of the subjects with bilateral hearing aid or bilateral cochlear implant (CI) experience significant difficulties in noisy environments [35].

For hearing in noise, one must discriminate the target speech from noise and then concentrate on speech while ignoring the noise. Certainly binaural hearing will facilitate this process. Ability of localization, detection and following target speech, suppressing the non-target sources, pay attention to one ear's inputs and suppress the other, judge about movement and the distance of sound source are related to binaural hearing. These researchers have designed a training method for subjects with bilateral CI. They utilized eight loudspeakers for presenting speech and noise from different angles to improve the localization and speech perception in noise. Loudspeakers were at the ear level and were located 140 cm from subjects. The training was comprised of determining sound locations and speech perception in noise. They presented 12 spondees in closed set and babble noise contained two speakers' voice (a female and a male). Presentation level for words was constant but noise level was set to the point that subject could recognize 50% of words correctly. The sounds like train and car horn and hand clap were used for localization training. All subjects did not show similar improvement: some had stronger improvement in localization ability than speech perception in noise and others showed more speech in noise improvement than auditory localization. Children with cochlear implant showed more improvement than adults with CI and this may be due to more significant neural system plasticity [35].

In another research the effects of ILD and ITD training under headphone (lateralization training) have been studied. Subjects trained for an hour a day in nine days. In general, the ILD and ITD discrimination ability increased but this improvement was slower for ILD than ITD and that means there is a different learning pattern for these two cues [36]. Cameron and Dillon introduced LiSN (listening in specialized noise) software for creating 3D auditory environment under headphone to measure auditory stream segregation in children and measure speech perception in noise in the children with suspected (C)APD [37], or at risk for (C)APD [38].

Speech perception in noise difficulty is very common in these children. Different cues help auditory stream segregation and one of them is sound localization that needs detection, perception and comparison of fine temporal and intensity difference between two ears. For identifying children with SusCAPD they used pitch pattern sequence (PPS) test, dichotic digit test (DDT), random gap detection test (RGDT), masking level difference (MLD) and listening in specialized noise-sentences test-sentence (LiSN-S), and if the score was less than 2 standard deviations below normative data, it was considered abnormal [37].

LiSN is comprised of presenting the target and competing sentences through headphone from different spatial locations. The subjects must concentrate only on target sentence and repeat it completely. In this test the child is asked to repeat sentences which are presented from 0 degree azimuth in presence of competing sentences and speech recognition threshold (SRT) is calculated. The competing sentence location changes between 0 to 90 degree (both right and left positions). Sometimes speaker of target and competing signal are the same but other times they are different. They conducted this research on nine children with SusCAPD who had listening problems in the classroom and had no hearing impairment, language learning, learning disability (LD) and attention deficit, and on 11 children with LD. In this study performance of children with LD was the same as control group, while children with SusCAPD could not take advantage of spatial disparity of target speech from competing signal. They emphasized that more research in this field is necessary. Also indicated that most children with LD do not have any problems in LiSN-S, therefore it is not logical to attribute listening problems in these children to (C)APD right away. The LiSN-S potentially is useful for evaluating auditory stream segregation problems. Subjects with auditory streaming problems need higher SNR for speech perception in noise [37]. They also introduced a software (LiSN & Learn) for spatial hearing training. In another study, they compared LiSN & Learn with Earobics auditory training method. Earobics software is one of the oldest software that improves children's literacy skills. Earobics improves phonemic awareness, auditory processing, phonetic skills, cognitive and linguistic skills. They concluded that LiSN & Learn method can improves the binaural hearing and spatial processing in children whereas Earobics cannot have this specialized effect [39].

In general, it is concluded that spatial hearing can help listeners to focus on target speaker in noisy environments [40,41]. The power of sound source segregation based on spatial location is very important in auditory scene analysis (ASA) and causes formation of individual auditory objects [40]. Sound localization, even in reverberant environments that changes binaural cues, can be improved by training [42,29]. In conditions where several sound sources exist, spatial information is particularly important for speech processing [43,44]. In fact binaural cues, help attending on one speaker in multi talker scene [45]. Moreover, listener knowledge about speaker's location, improves this spatial advantage [44,46].

Conclusion

Spatial hearing evaluation in children suspected to (C)APD is very important because spatial hearing disorder can cause speech perception difficulties in noisy places and this is the most common complaint of children with (C)APD. It is necessary to pay attention to diagnosis and rehabilitation of spatial hearing disorder in children with (C)APD.

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