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Neuroplasticity and the Auditory System

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Abstract

This chapter will present information on the central auditory nervous system with a special focus in the auditory pathways. The intrinsic and extrinsic aspects of neuroplasticity will be described, and the neuroplasticity of the auditory system will be presented in detail. These topics are the basis of the auditory training (AT) program for central auditory processing disorders.

Keywords: auditory pathways, neuroplasticity, auditory training

1. Introduction

1.1 The central auditory nervous system

The central nervous system is bilaterally symmetrical, and it is composed of seven main regions: the spinal cord, the bulb, the bridge, the cerebellum, the midbrain, the diencephalon, and the cerebral hemispheres. Each of these neural regions performs a number of specific functions. Additionally, each function, whether it is a sensory, a motor, or another integrative task, is performed by more than one neural pathway [1, 2].

The linguistic cerebral functions are mainly located in the auditory cortex, which is divided into four anatomically distinct lobes: the frontal, the parietal, the occipital, and the temporal lobe. The latter is responsible for the function of hearing as well as for various aspects of learning, of memory, and of emotions (**Figure 1**).

The cerebral hemispheres are characterized by two important organizational features:

- i. Each hemisphere is primarily related to specific sensory and motor processes on the opposite (contralateral) side of the body. The structure connecting the two hemispheres is the corpus callosum [2].
- ii. Although both hemispheres appear to be similar (in humans), they are not structurally fully symmetrical nor they have equivalent functions.

Broca, Wernicke, and Penfield were pioneers in unraveling the functions of the temporal lobe. Penfield found that a stimulation of primary auditory areas produced gross auditory sensations, whereas stimulation in the superior temporal gyrus produced altered perception of auditory sounds, illusions, and hallucinations.

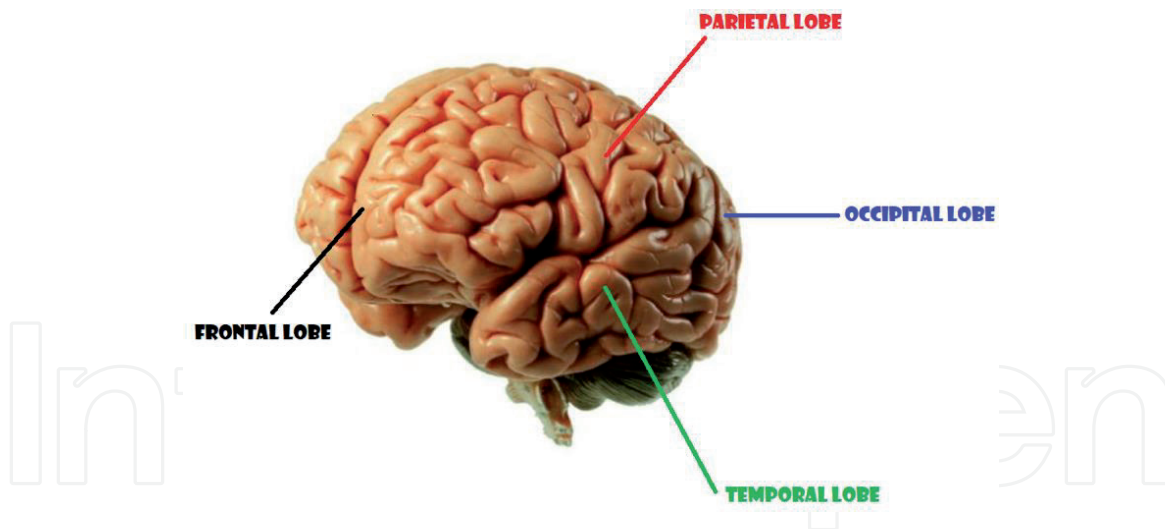


Figure 1.
The four cerebral lobes of the auditory cortex.

Studies on epileptic patients, whose hemispheres were separated by a section of the corpus callosum, have allowed us to understand numerous details related to the concept of hemispheric specialization [3].

An important contribution for the understanding of hemispheric function was achieved through the development of the Wada test [4]. The latter was developed in order to determine the dominant hemisphere for speech, so that inadvertent lesions of the speech centers, during neurosurgical procedures, could be avoided. During the test, the patient is instructed to count aloud, while sodium nitrite, a fast-acting barbiturate, is injected into the left or right carotid artery. The drug preferentially accesses the hemisphere on the same side as the injection, causing a brief speech dysfunction. If the dominant hemisphere's speech center is affected, the patient usually stops counting. With this test, the relationship between hemispheric specialization and laterality can be assessed, especially in left-handed subjects. Data in the literature [4] suggest that 96% of the right-handed people have dominant speech centers in the left hemisphere, while 15% of left-handed people have dominant speech centers in the right hemisphere. In some left-handed people, speech is controlled by both hemispheres. In such cases the administration of sodium nitrite does not suppress speech. Similar results were observed in trials involving hearing. When sounds were presented at the same time in both ears, it was found that in right-handed people the left ear performed better with nonverbal sounds.

The auditory system can be considered a high-performance signal-processing region, presenting a complex built-in hierarchy. Within the system each structure has a specific function, and progressing upwards along the pathways, these functions become more specific and dependent on the functional and physiological integrity of the previous structures. The auditory system plays an essential role for the communication among the members of the same species. Additionally, humans use the sensory inputs of the auditory system to identify different sounds leading to immediate actions, such as the status of alertness caused by the perception of siren sounds from police cars and ambulances.

From a simplified point of view, the auditory system consists of two areas, namely, the auditory periphery and the central auditory system. In each there are several structures which are stimulated when a sound stimulus is presented. Some researchers [5], however, have disputed this simple division of the auditory system suggesting instead a three-stage depiction:

- i. The periphery, which captures and converts the acoustic sound stimuli into electrical neural pulses.

- ii. The brainstem, which performs the initial processing of the information through modulation and interaction of the signals.
- iii. The thalamocortical region, which is responsible for more advanced functions and produces emotional, cognitive, and linguistic responses from the acoustical stimuli

The efficiency of this set of interconnected structures depends primarily on the auditory experience. The simplest auditory task is influenced by high-level functions that include motivation, memory, and decision-making [6].

From a functional point of view, the following functions (among others) are assigned to CANS: the ability to detect and discriminate sound sources, the separation of acoustic stimuli from the background noise, the process of understanding the incoming stimuli, and the process of recognizing the stimuli as something familiar, through memory connections [7].

There are two pathways in the CANS: the ascending (afferent) and the descending (efferent) pathway. The afferent pathway is the path that an impulse, generated in the hair cells, travels along to the auditory cortex, whereas the efferent auditory pathway is a similar path, but in the opposite direction, conducting impulses from the auditory cortex to the hair cells [8].

The afferent and efferent pathways act in an integrated way. The afferent auditory pathway has a bilateral and predominantly contralateral auditory representation. The propagation of auditory information occurs via the cochlear nuclei, superior olivary complex, lateral lemniscus, inferior colliculus, and medial geniculate body up to the auditory area of the temporal lobe in the cerebral cortex. The efferent auditory pathway is composed by the medial and lateral olivocochlear bundles which have anatomical and physiological differences, coordinating the independent function of the two ears [9]. The function of the efferent auditory feedback includes the electrical modulation of the outer hair cells in the cochlea, the reduction of the cochlear nerve action potentials, the protection against noise, the localization of a sound source, the improvement in the detection of sound sources in noisy environments, and the focusing of attention to the incoming acoustic stimuli, which is less effective in patients with tinnitus [9, 10] (**Figure 2**).

It should be emphasized that information from sound stimuli is sent to the brain through both ipsilateral and contralateral pathways, the result of which provides data on signal timing and stimulus intensity. These are passed on to associative areas which process the data in a differentiated way, with the left hemispheric dominance for the processing of language and the right hemisphere for the process of melody. The data on the hemispheric dominance are derived from studies in patients with cortical lesions revealing a loss of recognition of family songs and prosody in patients with right-sided injury and poor recognition of verbal language and symbolic noise in patients with a left lesion [11].

Rees [12] identified auditory perception deficits as one of the causes of language disorders and concluded that auditory abilities seem to play a major role in language and learning. Lubert [13] reported that a deficiency in the ability to detect acoustic characteristics of an auditory signal was overwhelmingly important that affected children never achieved good performance in language tasks.

There is a strong interest in the literature on the impact of auditory processing deficits on language skills and reading [14]. However, the nature of the relationship between auditory and speech processing continues to be debated [15]. The starting point for differentiating auditory processing from that of language consists of a knowledge of acoustic, phonemic, and linguistic characteristics in a behavioral and neurological way. Individuals who have primary deficits in their auditory perceptual

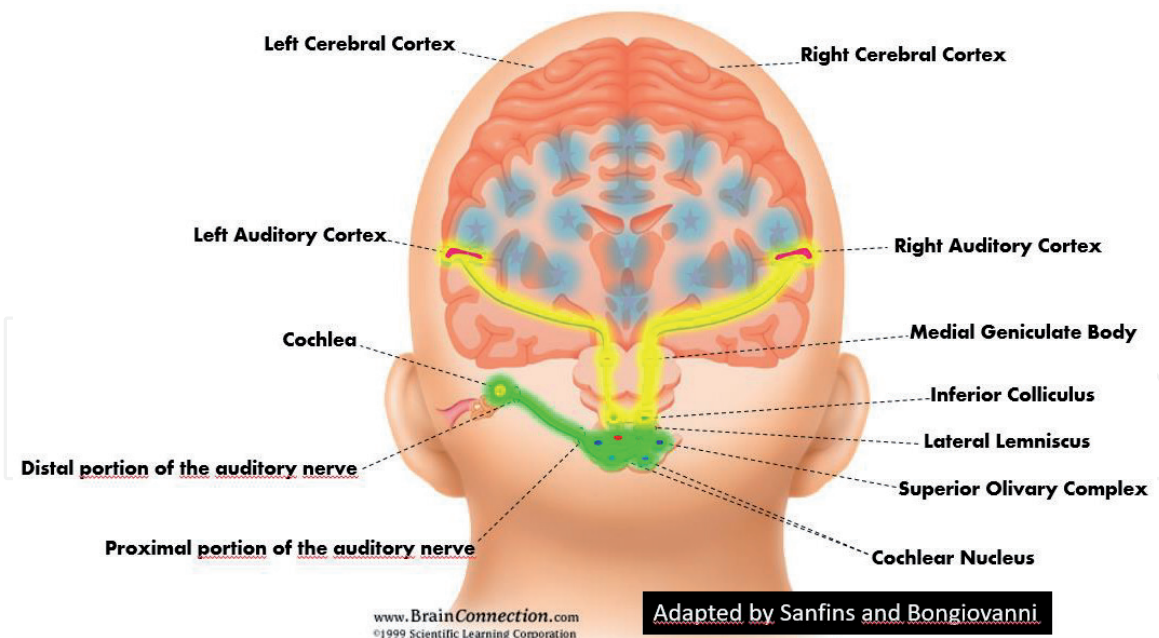


Figure 2.
Schematic representation of the auditory pathways.

abilities therefore have similar symptoms to those who have other pathologies such as dyslexia and attention deficit hyperactivity disorder, and as a consequence they may have attention and executive deficits as well [16].

1.2 Neuroplasticity

The human brain has certain time periods—called critical periods—during which it is conducive to neuroplasticity. In these critical periods, capacities are shaped, perfected, or altered as a result of experience.

In humans, cortical neuroplasticity is most pronounced in the first years of life. During this developmental period, cortical neurons are extensively stimulated, and in this way, synapses mature and developed. In addition, various sensory and cognitive systems interact and adjust their functional properties based on prior experience and learning. Younger brains seem to be more able to change as a result of persisting stimuli [17]. These are usually related to changes (i) in behavior, (ii) in the environment, and (iii) in the neural processes.

Over the course of a lifetime, a lack of experience during critical developmental periods can hinder learning [19]. A critical period can be described by the simultaneous presence of these three conditions:

- i. The information must be reliable and extremely precise.
- ii. The neural connections need to be intact to be able to process information, either through inhibitory and/or excitatory connections [18].
- iii. Mechanisms must be in place to sustain the plasticity process, such as modifications in the morphologies of axons and dendrites and modification to synaptic connections.

It should be emphasized that simple skills require the use of less specialized neural circuits, while more complex abilities depend on the use of more specialized ones. The simplest neural circuits need first to be activated and to be efficient, before new neural circuits can be made reliable [20, 21].

Stimulation of any skill during the critical period of development is an extremely important factor for the success of any intervention process. However, it is important to note that adult brains also have a proven ability to change. Thus, different neuronal systems can be activated regardless of the age of the individual [22, 23].

Activities which depend on the integration of different neuronal systems engage in a multimodal cerebral activation, and thus they can enhance neuroplasticity. A good example of such multisensory stimulation is the process of learning to play music [24–26]. Paraskevopoulos et al. [25] demonstrated that musicians who started their training as young adults had a greater activation of the prefrontal cortex than musicians with only short-term training. Data in the literature suggest that a wide range of beneficial effects can be manifested by elderly musical students, including improvements in attention, memory, motor function, executive function, creativity, anxiety reduction, and visual scanning [27–30].

Intrinsic and extrinsic factors can cause changes in brain cells. Data from the literature suggest that new neurons are present after 6–8 weeks from the time an adult undertakes a new skill [31, 32]. It is therefore suggested that learning and maintaining a new activity should be encouraged in order to activate neural circuits and create new synapses.

Neuroplasticity has been associated with a delayed onset of dementia. Broolmeyer et al. [33] state that brain plasticity should be made a priority in dealing with individuals who have dementia. Concomitantly, age-related cognitive decline can be delayed, interrupted, or even reversed by introducing tasks that involve multimodal neuronal stimulation.

By recognizing the importance of neuroplasticity, professionals involved in rehabilitation are encouraged to turn their efforts toward stimulating, motivating, creating, and developing new strategies for the treatment of their patients.

1.3 Neuroplasticity of the auditory system

Like other systems, the development of the central auditory nervous system depends on a critical period during the first years of life when responses to different stimuli and sound environments are gradually established. In the auditory system the capacity for anatomical and functional modification is called auditory neuroplasticity [34].

The cortical areas that encompass the auditory system develop rapidly in the first years of life, due to an abundance of neuronal connections [35, 36]. At approximately 4 years of age, the neurons responsible for hearing go through a process which is called pruning, where neurons and synapses which are not activated are eliminated from the system [37].

Although the plasticity due to experience is far greater in the first years of life, it is known that the auditory system has some malleability throughout life [37]. Sharma et al. [38] established that there was a difference between what is known as a critical period and a sensitive period. According to Sharma, the critical period ends suddenly, and the neural system is unable to adapt to stimuli; in contrast, the sensitive period is an ideal neuroplastic period during which sound can be introduced into the auditory cortex and promote normal age-appropriate development.

Preterm infants who remain long periods in a neonatal intensive care unit (NICU) are often exposed to high ambient noise levels, generated by the hospital equipment. The high-frequency sounds can cause acoustic trauma and hamper the proper development of the central auditory nervous system [39]. According to Zhang et al., excessive noise at critical periods of development can lead to impaired cortical tonotopic maps, resulting in a reduction in neural synchrony and a

decreased sensitivity to particular frequencies [40]. In addition, the extra noise can mask speech sounds, thereby impoverishing the auditory experience. As a result, infants can become more sensitive to noise and focus their attention on this type of sound stimulus instead of ignoring it and focusing on speech [41]. Among preterm infants there is a high rate of impairment of hearing, language, and attention; on the other hand, a home environment rich in post-NICU auditory and linguistic stimuli favors auditory neuroplasticity, meaning that premature infants then have a good chance of developing normal speech, language, and learning [42].

One way to observe plasticity in the auditory system is by monitoring patients undergoing cochlear implantation. Even after a period of auditory deprivation due to hearing loss, it is possible for the brain's auditory system to reorganize and develop better hearing abilities. Research on children implanted at the age of 3, 5, and 7 years has demonstrated that cortical auditory development can be mixed, with some children presenting cortical auditory evoked potential responses (notably P1) within normal limits, while others do not seem to achieve normal central auditory maturity. These findings are consistent with positron emission tomography (PET) imaging tests performed before and after cochlear implantation. It appears that 3.5 years of age is the end of the sensitive period for cochlear implantation in children with congenital deafness; this age is approximately when the observed exponential increase in synaptic density ends and begins to decrease [35]. Beyond 7 years of age, neuroplasticity in the central auditory system is significantly reduced; if new sounds are introduced after this time, the auditory cortex is unable to process auditory information normally [38, 43]. Research on the development of speech and language skills in children has indicated significantly better outcomes in those who received cochlear implants at younger ages [44, 45].

Neuroplasticity can be observed in individuals with central auditory processing disorder (CAPD) who have undergone auditory training. Training is a therapeutic procedure involving auditory stimulation that leads to reorganization (remapping) of the cortex and brainstem, improving synaptic efficiency and increasing neural density. These neurophysiological changes, reflected on behavioral changes, have encouraged the use of this rehabilitation strategy [46–48].

1.4 Auditory training in central auditory processing disorder

It is well established that listeners with CAPD exhibit diverse behaviors such as poor listening skills, difficulty learning through the auditory modality, difficulty following auditory instructions, difficulty in understanding when there is background noise, requesting information to be repeated, poor auditory attention, easily distracted, deficits with phonological awareness and phonic skills, weak auditory memory, delayed response to verbal stimuli, and difficulty with spelling, reading, and learning [49].

A diagnosis of impaired central auditory processing is done by applying a battery of behavioral and electrophysiological procedures. The results provide information about the physiological mechanisms in the auditory system and a profile of abilities that are altered and those that are preserved. Based on this diagnostic information, rehabilitation should start as soon as possible in order to minimize the effects of CAPD on language development. One strategy is the use of auditory training (AT), defined as the set of (acoustic) conditions and/or tasks designed to activate auditory and related systems such that neural connections and the associated auditory behavior is improved [50].

The general aim of AT when applied to individuals with CAPD is to improve auditory skills such as sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of audition, and auditory

discrimination against competing acoustic signals [51]. Formal and informal AT procedures are conducted by audiologists in the clinical environment. The difference between them is that formal training needs to be acoustically controlled, with a strict control over the stimulus generation and presentation. The combination of formal and informal AT procedures offers a flexible approach which presents positively effective outcomes [50].

The management of CAPD requires a multidisciplinary team, since the pathology commonly appears with other disorders (attention deficit/hyperactivity disorder), learning and language disabilities, or dyslexia. The multidisciplinary team members are often speech-language pathologists, psychologists, neuropsychologists, neuropsychiatrists, teachers and parents, or other specialists involved in the child's overall care [52] (**Figure 3**).

The therapy to enhance auditory skills should be evidence-based, individualized, and segmented into bottom-up and top-down treatments. A bottom-up approach is based on the premise that difficulties in central auditory processing (CAP) lead to impaired auditory perception, language, reading, and communication. The objective of the bottom-up therapy is to improve speech perception. The top-down approach includes auditory cohesion, auditory attention, and metacognitive and metalinguistic activities [52, 53].

The AT program should follow some important principles:

- It should be frequent, challenging, and motivating, using age and language appropriate for the patient.
- It should include diverse tasks to maintain motivation.
- It should be gradual in difficulty over time.
- It should employ a follow-up on acquired responses (achieving response rates >70% is an indication that the task needs to be more demanding).
- It should use monitoring and feedback based on psychophysical, electrophysiological, and questionnaire-based information [50, 52].

The results obtained in the diagnostic battery will guide the therapeutic planning, which should include tasks aimed at discriminating sound intensity, frequency, and duration; phoneme discrimination; time perception discrimination; temporal ordering and sequencing; pattern recognition, location, and lateralization; and recognition of auditory information in the presence of competitive signals. Other aspects may include study of interhemispheric information transfer and binaural listening [51, 54].

In addition, modifications are important depending on the environment. To improve access to auditory information outside the therapy room, teachers and parents also need to help with CAPD treatment strategies. Simple changes may bring many benefits to learning. Options may include:

- i. Preferential seating
- ii. Addition of visual cues
- iii. Clear language
- iv. Making frequent checks for understanding

- v. Repetition or rephrasing
- vi. Multimodality cues and hands-on demonstrations
- vii. Pre-teaching of new information and new vocabulary
- viii. Provision of a notetaker
- ix. Gaining attention prior to speaking
- x. Positive reinforcement
- xi. Reduce background noise
- xii. FM systems

Monitoring progress of the patient is important since it allows the therapist to measure the appropriateness of the AT program and provides a basis for feedback to the patient and parents [50]. Ideally, three types of monitoring should be employed to measure auditory changes: psychophysical, electrophysiological, and questionnaires. These measures should be obtained before and after hearing training. Several questionnaires are available and can be answered by the patient and/or individuals interacting with him or her, such as parents, teachers, and other professionals.

Several questionnaires are described in the literature, such as the Children's Auditory Performance Scale (CHAPS) [55, 56], Screening Instrument for Targeting Educational Risk (SIFTER) [56, 57], Children's Home Inventory of Listening Difficulties (CHILD) [58], and the Scale of Auditory Behaviors (SAB) [58].

A large number of studies provide definitive evidence for the plasticity of the auditory system evidenced by behavioral changes in both animals [59–61] and in humans [62–68]. A recent study by Donadon et al. [69], whose objective was to investigate auditory training in children and adolescents suffering from otitis media

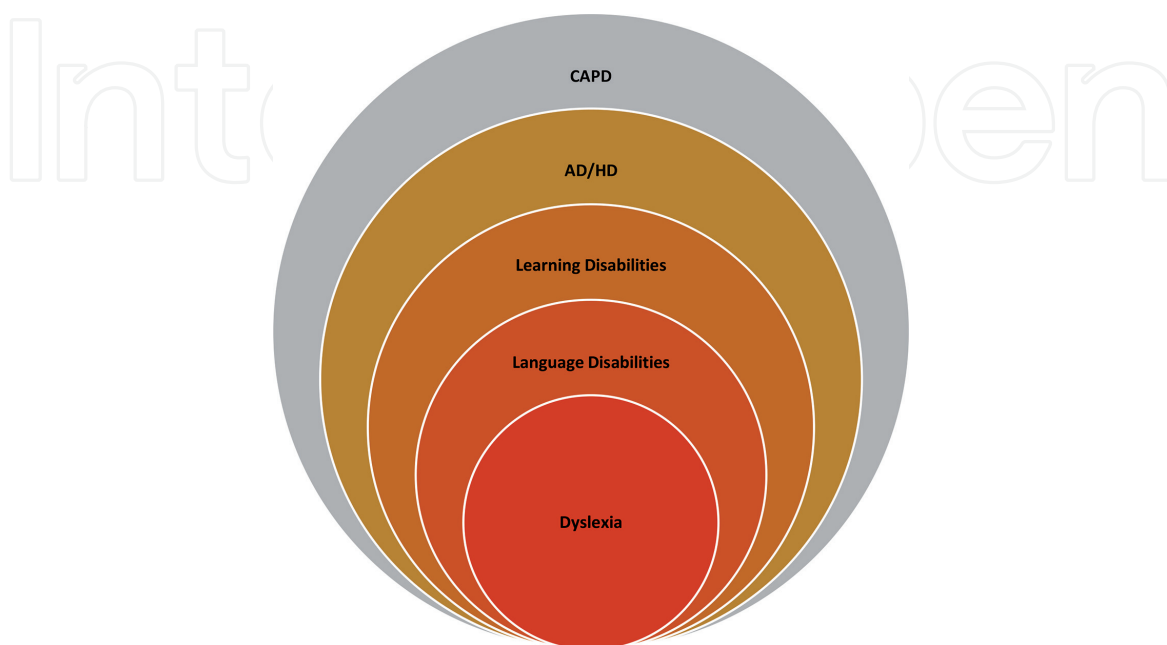


Figure 3.
CAPD and associated pathologies.

with a documented history of bilateral ventilation tube insertion, highlighted some aspects of auditory neuroplasticity. According to the data from the study, the participants were randomly divided into two groups: (i) auditory training and (ii) visual training. In the behavioral tests during the pre-intervention evaluation, no statistical differences were detected. However, after the auditory training program, there was an improvement in the subjects' performance for auditory abilities. In addition, comparing the two types of intervention (visual vs. auditory), the behavioral tests revealed better responses to the post-intervention auditory training. The results, assessed through behavioral tests on subjects with a history of bilateral otitis media, suggest that auditory training provided beneficial gains for all auditory abilities.

2. Conclusion

The central auditory nervous system is responsible for the processing of auditory information. It is highly complex and plastic, being able to reorganize itself in response to auditory stimulation. Auditory training promotes behavioral and electrophysiological changes due to the neurophysiology of the brain's plasticity. The latter enables the positive performance of the auditory training, which is an important rehabilitation strategy for individuals with central auditory processing disorders.

Abbreviations

AD/HD	attention deficit/hyperactivity disorder
AT	auditory training
CANS	central auditory nervous system
CAP	central auditory processing
CAPD	central auditory processing disorder
CNS	central nervous system
critical period	the time during which the neural system is unable to adapt
sensitive period	the ideal period for neuroplasticity to occur
Wada test	a test for determining the dominant hemisphere for speech

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