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Beyond the ear: central auditory plasticity

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There is a current surge of interest in understanding central auditory plasticity and how these principles relate to aural rehabilitation and to learning in general. Knowing more about the science underlying rehabilitation might advance the way scientists and clinicians approach rehabilitation. For this reason we review basic principles of central auditory plasticity and how these principles are being applied to study populations with auditory-based communication disorders. Specifically, we discuss how principles of plasticity relate to aural rehabilitation. Therefore, the effects of auditory deprivation and auditory stimulation on central auditory mechanisms are reviewed.

KEY WORDS: Auditory training - Auditory plasticity - Speech perception - Auditory evoked potentials - Learning disorders.

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What happens to the central auditory system when a person loses their hearing? Does reintroducing sound, following a period of auditory deprivation, alter neural response patterns beyond the ear? In people with healthy ears, how does listening experience alter the brain's response to sound? Until recently, little was known about the effects of auditory deprivation or stimulation on central auditory mechanisms. However, there is increasing evidence from human and animal studies that the central auditory system is "plastic"; primary sensory cortices change with experience.

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There is a current surge of interest in understanding central auditory plasticity and how these principles relate to aural rehabilitation and to learning in general. Learning more about the science underlying rehabilitation might advance the way scientists and clinicians approach rehabilitation. For this reason we review basic principles of central auditory plasticity and how these principles are being applied to study populations with auditory-based communication disorders.

"Neural plasticity" is a term used to describe alterations in the physiological and anatomical properties of neurons in the brain in association with sensory stimulation and deprivation. Depending on the experience, mechanisms of plasticity can involve synaptic changes that occur rapidly, or slowly over a longer period of time. Most importantly, experience-related changes in the brain have perceptual consequences. For example, when animals are trained to discriminate new sounds, systematic changes in neural activity accompany improved behavioral performance.[1-8] In animals, experience-related changes in central auditory function are examined using direct recordings from various structures along the auditory pathway. These techniques are invasive and therefore inappro-

priate for studying comparable changes in the human auditory system. Fortunately, functional imaging, magnoencephalography (MEG) and auditory evoked potentials (AEPs) have emerged as non-invasive tools for assessing neural response patterns in humans. All of these techniques are useful for studying neural processing of sound; however, AEPs are particularly sensitive neural indices to neural activity in response to rapidly changing signals such as speech. Unlike imaging tools, AEPs can be recorded quickly and inexpensively in most clinical settings. This feature makes AEPs suitable tool for assessing central auditory function in clinical populations with auditory-based communication disorders. For this reason, identifying AEPs that reveal central auditory dysfunction, as well as central auditory plasticity is a current focus of clinical research.

Here we integrate both animal and human research findings in order to communicate principles of central auditory plasticity and how these notions relate to clinical populations with auditory communication disorders.

The effect of hearing loss on the central auditory system

Peripheral hearing loss alters frequency and timing codes along the auditory pathway. Not only does cochlear hearing loss compromise stimulus audibility, peripheral pathology also alters the way spectral and temporal information is coded along the auditory pathway. The consequences of peripheral pathology can be seen throughout the central auditory system; including portions of the cochlear nucleus, but especially in the inferior colliculus, and primary auditory cortex.[9-23] Animal studies have shown that auditory deprivation disrupts the normal tonotopic organization of the central auditory system. For example, age-related hearing loss results in changes in how frequency is "mapped" in the central auditory system. When deprived of normal peripheral input, intact regions of the tonotopic map, adjacent to the impaired regions, often become responsive.[24, 25] It has been suggested that remapped frequency representation could result in perceptual confusions. However, it is also possible that increased neural representation might provide useful information but in a novel form.[26]

Central auditory reorganization has been shown to take place following experimentally induced unilateral hearing loss in animals.[16, 18] Although less is known about the effects of peripheral pathology on the human auditory system, electrophysiological and magnoencephalographic evidence suggests that auditory deprivation induces neural changes in human auditory systems as well.[27-29] For example, Ponton *et al.* (2001) used an AEP called the N1-P2 complex to study the central effects of profound unilateral deafness. The N1-P2 complex is a long-latency AEP that reflects synchronous neural activation of structures in the thalamic-cortical segment of the central auditory system. Depending on the characteristics of the stimulus used to evoke the response, the negative peak (N1) occurs 100 ms following stimulus onset and is followed by a positive peak approaching 200 ms (for a review see Hyde, 1997).[30] Typically, N1 and P2 responses are larger in amplitude when measured over the hemisphere contralateral to the ear of stimulation. When Ponton *et al*. examined patients who had experienced profound unilateral deafness as a result of acoustic neuroma removal or other otologic disorders; the typical asymmetrical response was altered. Specifically, N1 amplitude was larger in amplitude ipsilateral to the intact ear in patients with unilateral hearing loss (Figure 1). Cross sectional analyses recorded from the unilaterally deaf also revealed that changes in cortical activity occurred gradually and continued for at least two years after the onset of hearing loss. Ponton *et al*. speculated that increased neural activity ipsilateral to the normal-hearing ear might have a compensatory purpose facilitating sound localization. Converging evidence from both human and animal studies do suggest that underlying neural mechanisms regulating spatial hearing are plastic. Humans are able to learn to associate the altered localization cues with directions in space; similarly, ferrets raised and tested with one plugged ear learn to localize as accurately as control animals if the ear-plug is left in place for several months.[31]

The effect of stimulation on the central auditory system

Just as central auditory plasticity is seen as a consequence of auditory deprivation, changes in the central auditory system are known to occur in response to various forms of auditory stimulation.[32-34] Both in humans and in animals, electrically stimulating the auditory system alters physiological response prop-

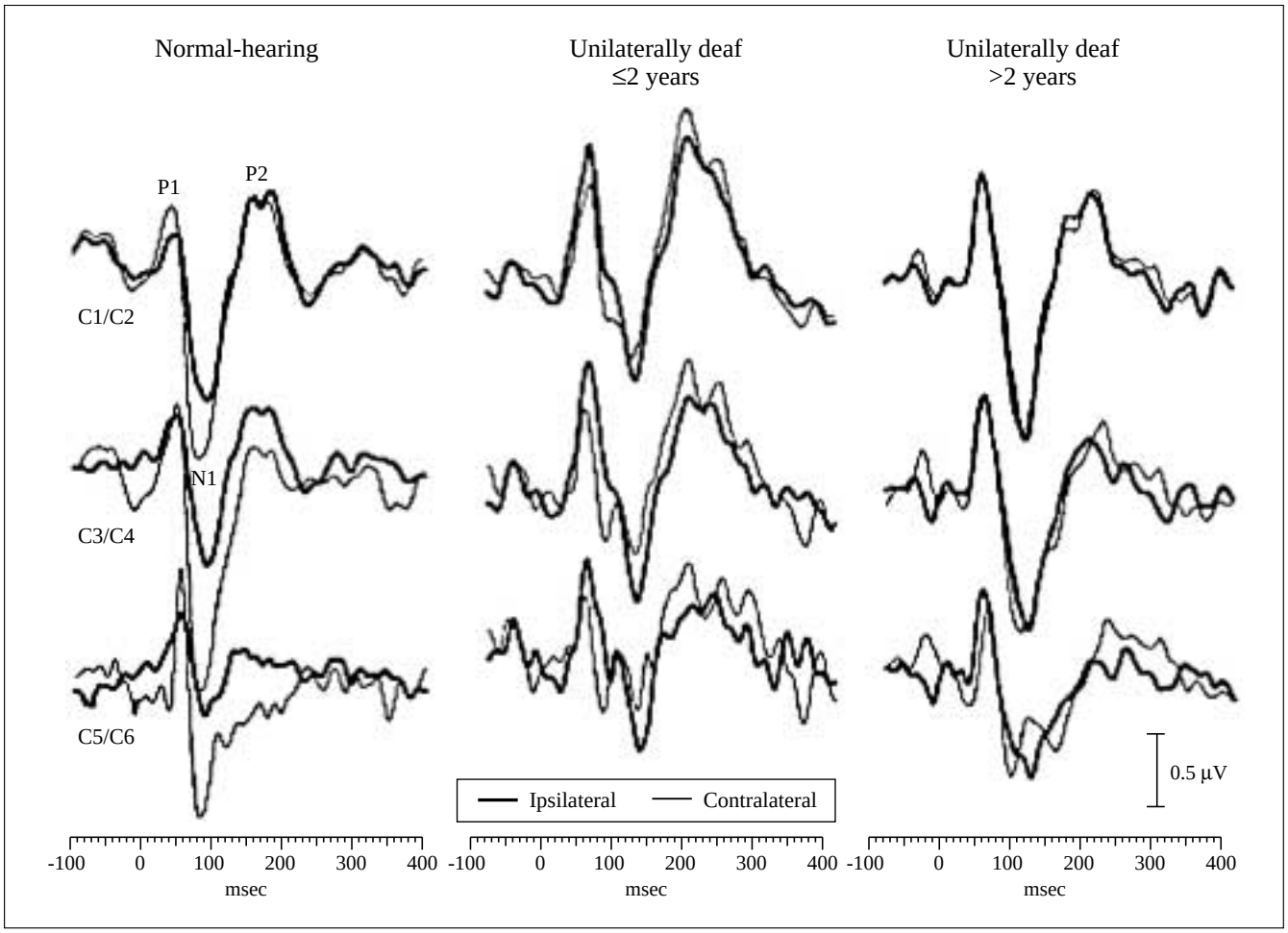

Fig. 1.—Waveforms recorded using homologous ipsilateral-contralateral electrode pairs from a normal-hearing individual, an individual that experienced unilateral deafness ≤2 years, as well as an individual with unilateral deafness >2 years. Ipsilateral and contralateral response amplitudes become more equal as the time since onset of deafness increases. Reprinted and modified with permission from Ponton *et al.*, 2001.

erties and improves perception. AEPs have been used to study changes in cortical activity in adults and children following cochlear implantation.[35-41] For example, Ponton *et al*. (1996) examined auditory system plasticity in children fit with cochlear implants. Using long-latency cortical AEPs, Ponton *et al.* found that children who use cochlear implants evoked response patterns that are immature. Interestingly, the degree of immaturity was proportionate to the number of years of auditory deprivation thereby suggesting that the auditory system does not fully mature without stimulation. Because the reintroduction of sound, through electrical stimulation, resumed the normal maturational process, Ponton *et al*. concluded that the auditory system retains its capacity for change (plasticity) during the period of deafness.

Training experiments provide another opportunity to study central auditory changes associated with auditory stimulation. Numerous animal studies have shown that auditory training modifies neural activity.[1-3, 5-7, 42-45] Recanzone *et al*. (1993) [7] trained owl monkeys to discriminate small tonal frequency differences. After several weeks of training, monkeys improved their ability to discriminate the trained frequency and significant changes in the tonotopic arrangement of the auditory cortex were seen. Specifically, the area of the cortex that corresponded with the trained frequency was significantly larger than corresponding frequency

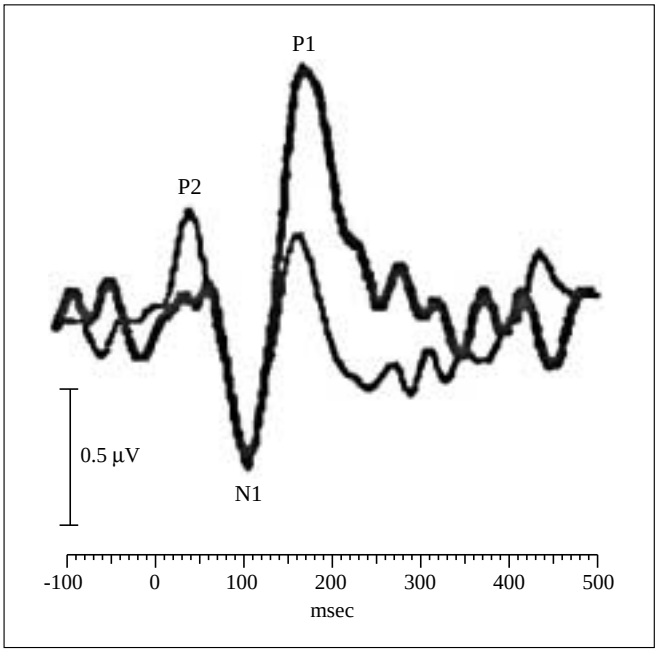

Fig. 2.—Pre- and post-training mean waveforms measured from electrode Cz. Pre-training waveforms are thin. Post-training waveforms are thick. As performance improved, N1-P2 peak-to-peak amplitude increased. Reprinted and modified with permission from Tremblay *et al*., 2001.

areas in the monkeys that were not trained. These findings, and others, inspired a new wave of research examining whether comparable brain-behavior relationships exist in humans.

Similar training effects have been observed in humans. When spectral or temporal cues are enhanced with auditory training, training-related changes in neural activity are recorded.[46-51] Figure 2 illustrates the N1-P2 complex before and after training. In this study, English speaking participants were trained to perceive two /ba/ stimuli that differed by 10 ms of prevoicing. Pre-voiced stimuli are used phonemically in languages such as Hindi and Spanish, but not English. Therefore, prior to training, perception approximated chance, and N1-P2 peak-to-peak amplitude was small for English speaking untrained listeners. However, when participants were trained to identify the two stimuli as being different from each other, perception improved and N1-P2 amplitude increased. In a control condition, participants were tested and then re-tested without intervening training and no significant physiological or perceptual changes occurred. Because this study demonstrated that N1-P2 complex reflects training-related changes in neural activity, long-latency AEPs are now being used to study perceptual changes in people who use cochlear implants.[52]

On the surface, auditory training may not resemble stimulation associated with cochlear implant use; however, there are similarities. During auditory training the objective is to improve the perception of acoustic contrasts. In other words, persons are taught to make new perceptual distinctions. Hearing aids and cochlear implants deliver a modified signal to an impaired, and thus reorganized, auditory system.[53, 54] Therefore this modified signal is a "new" signal that is likely stimulating "new" neural response patterns in the central auditory system. Even if the central auditory system is capable of reflecting modified spectral and temporal information, variability may lie in the individual's ability to integrate these new neural response patterns into meaningful perceptual events. In fact, many investigators suggest that some of the perceptual deficits experienced by hearing impaired individuals may be due to the inability to make use of these modified cues.[55-63] As a result, training studies have provoked new theories about performance variability in persons using cochlear implants and hearing aids. That is, rather than solely looking at the hearing device and what technological changes can be made to improve performance, we must also consider each individual's capacity for neural change. In other words, for some people, performance variability may be related to central auditory plasticity rather than the hearing device. If this is true, then perhaps it may be possible to predict who may or may not be benefit from using a cochlear implant or hearing aid, and who may need additional rehabilitation such as auditory training. Similar approaches are currently being used to study normal-hearing populations with auditory-based learning problems.

Children with auditory-based communication problems

Approximately, 9% of children in the United States are diagnosed with reading and learning disabilities. Because many people with learning problems experience difficulty discriminating fine-grained acoustic differences found in certain stop consonants, it has been hypothesized that a subset of these children have basic differences in the way their brains encode acoustic components of speech.[64, 65] For example, Kraus *et al*.[66]

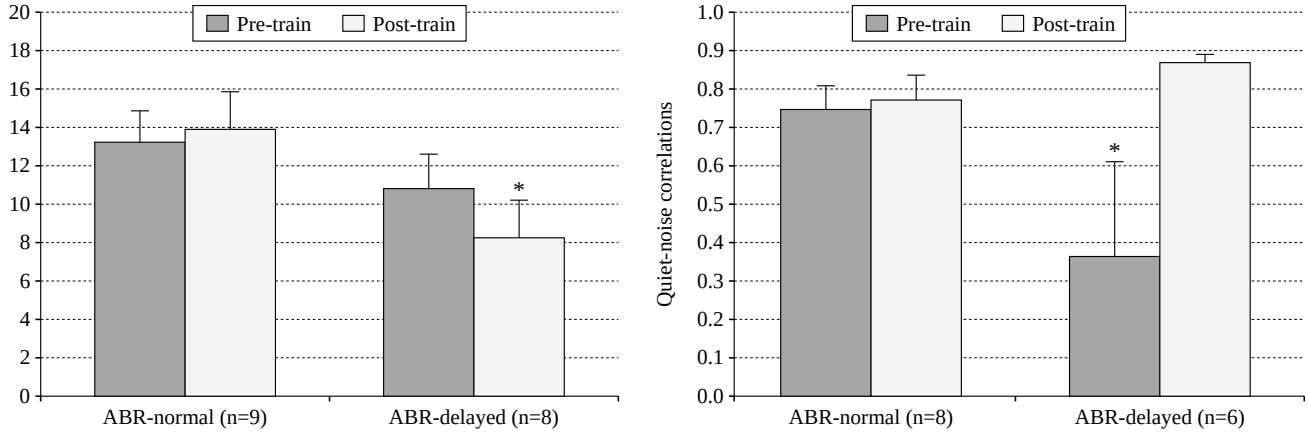

Fig. 3.—A) Following training, children with learning problems who had delayed brainstem responses showed improvement (lower just-noticeable difference score) in the discrimination task while scores for the children with learning problems and normal brainstem recordings did not change. B) Prior to training, children with learning problems and normal ABR responses showed better correlations of responses recorded in quiet and noise. Only the children with delayed latencies in the auditory brainstem recordings showed improvements in quiet-to-noise correlations following training. Reprinted with permission from King *et al.*, 2002.

found that children with learning problems have more difficulty detecting rapidly changing spectral cues that differentiate the speech sounds /da/ and /ga/. However, these same children have less difficulty discriminating slower duration differences that are critical for discriminating /ba/ and /wa/. Consistent with the perceptual differences, cortical AEPs were abnormal for the children when evoked by the /da-ga/ but not the /ba-wa/ stimuli. In contrast, children without learning problems showed no perceptual or physiological impairments for either stimulus contrast.

Because laboratory-based experiments have shown that training can improve perception, numerous treatment strategies for dealing with perceptual problems have become a focus in neuroscience research. Most recently, computer—based training programs have emerged in clinical settings across the country. These programs are designed to capitalize on the plasticity of the system with the expectation that auditory-based learning disorders, and the underlying neural mechanisms, can be modified through training. Furthermore, studying children who participate in such training programs provides an important opportunity to study neurophysiologic and perceptual changes associated with learning.

At the present time, the efficacy of these programs is not uniform across children, and it is unclear which kind of training, for which profile of deficit, results in perceptual improvement. However, knowing which children might benefit from training, and how training may alter the neural representation of sound at various levels of the auditory pathway will undoubtedly improve the way we assess and remediate children with auditory-based communication problems. For this reason, subjects with auditory-based learning problems who were participating in a commercial training (Earobics) regimen were recently evaluated pre and post-training using a number of behavioral and physiological measures.[67] Synchrony of auditory brainstem neurons was shown to differ between normal children and some of the children with learning problems. In addition, background noise had a deleterious effect on cortical responses in children with learning problems.[68] Most importantly, according to a small sample of children, auditory training improved perceptual abilities for children with abnormal brainstem responses and impaired perception.[67] Furthermore, children with learning problems who practiced with auditory training software exhibited plasticity of neural encoding of speech sounds at the cortical, but not subcortical, level of the auditory pathway. This plasticity was accompanied by perceptual and cognitive gains.[69] Figure 3 shows pre- and post-training changes in speech-sound perception as well as cortical AEP responses.

To summarize, children with abnormal ABR responses showed significant training-associated improvements in speech-sound perception and also

increases resistance to deleterious noise as shown in cortical responses. Taken together, these data suggest that certain auditory-based learning deficits may originate from a disorder in auditory neural timing at the brainstem level. Therefore, measures of auditory based synchrony, using speech stimuli, could be used to identify young children at risk for acoustic-phonetic-based learning problems, as well as separate out those children who would likely benefit from auditory training programs.

Finally, identifying the brain-behavior relationship in children with perceptual disorders might help identify abnormal processes in populations experiencing similar perceptual deficits. For example, older adults experience difficulties with speech understanding that cannot be explained by age-related hearing loss or cognitive decline.[70] Moreover, older adults have difficulty understanding speech-sounds, especially in the presence of noise.[71] Numerous studies hypothesize that age-related deficits in speech understanding are related to a decline in the temporal resolution power of the auditory system and there is increasing evidence that aging does alter the neural representation of time-varying acoustic cues.[51, 72, 73] For example, using an auditory brainstem response (ABR) forward masking paradigm, it has been shown that older listeners need a longer gap width for recovery of the probe response.[74] Cortical responses elicited by speech signals that contain a gap of silence also elicit abnormal response patterns in older adults.[51] Taken together, these findings suggests that temporal processing problems might underlie some of the speech perception difficulties experienced by older adults. Moreover, like children, older adults might be able to improve their ability to understand speech through auditory training.

Conclusions

In conclusion, animal and human work have established that the auditory system is plastic. Not only does this body of literature enhance our understanding of brain-behavior relationships, it provides scientific evidence to support clinical practices such as early identification, early intervention and aural rehabilitation. Even though the clinical world has developed practices assuming the "use it, or lose it" philosophy, we are only beginning to uncover the scientific principles underlying these beliefs.

Most importantly, these scientific discoveries will likely change the way we assess and remediate people with auditory-based impairments. Knowing that the brain is plastic helps justify the need for early identification because there is increasing evidence that the capacity to change decreases with age.[75] As we learn more about what neural mechanisms are impaired, we will also learn how to optimize sensory experiences and take advantage of the plastic nature of the auditory system.

Finally, from a neuroscience perspective, combining brain and behavior measures provides the opportunity to study learning. Whether it is speech-sound learning, or second language learning, we are beginning to understand how experience shapes behavior.

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Riassunto

Oltre l'orecchio: plasticità uditiva centrale

Attualmente gli sforzi di numerosi ricercatori sono volti a comprendere i principi della plasticità uditiva centrale e i loro rapporti con la riabilitazione uditiva e, più in generale, con l'apprendimento. Una migliore conoscenza dei presupposti scientifici della riabilitazione uditiva potrebbe portare a un migliorato approccio, scientifico e clinico, nei confronti della riabilitazione stessa. Per tale motivo, in questo lavoro vengono esaminati i principi basilari della plasticità uditiva centrale e il modo in cui questi principi vengono applicati allo studio dei pazienti con disturbi della comunicazione su base uditiva. In particolare, vengono discussi i rapporti fra principi basilari della plasticità e riabilitazione uditiva. A questo scopo, vengono riveduti gli effetti della deprivazione e della stimolazione uditiva sui meccanismi uditivi centrali.

PAROLE CHIAVE: Potenziali uditivi evocati - Apprendimento, disordini - Linguaggio, percezione - Riabilitazione - Plasticità uditiva - Training uditivo.

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