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Cochlear implants and neuroplasticity: linking auditory exposure and practice

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Hearing loss is primarily a brain issues, not an ear issue. Technology, e.g. cochlear implants and hearing aids are necessary to reach the brain of a child with hearing loss in order to create a neural structure for listening, language and literacy. The brain requires a great deal of auditory exposure and practice to develop the strong neural connections that serve as a platform for knowledge acquisition. By integrating research from multiple fields, this article links experience dependent plasticity with the amount of auditory practice that is necessary to generate and change neural pathways for children with hearing loss.

Keywords: cochlear implants, critical periods, deafness, early auditory intervention, neuroplasticity

For hundreds' of years, conversations about hearing loss have focused on the ear. Today, the conversation centers on the brain because we hear with the brain; the ear functions to channel sound to the brain. The challenges posed by hearing loss result primarily from problems in the peripheral auditory system that keep sound from reaching the brain. If sound can be transmitted to the brain in a timely and expeditious fashion, via technology, then the negative consequences of unmanaged hearing loss on speech, language, and literacy development can be averted.

Basic science research has offered increasingly robust information about neural plasticity and how our current technologies function as 'brain access tools' rather than as ear stimulation devices. Once auditory brain exposure is maximized through technology, the next question becomes how much acoustic stimulation does the brain require to develop effective auditory neural pathways, and when and how should that stimulation occur?

By integrating research from multiple fields, this article links experience-dependent plasticity with the amount of auditory practice that is necessary to generate and change neural pathways. It is likely that we have substantially underestimated the amount of practice time that is actually required to wire and re-wire the brain for high performance.

Auditory neural development

The brain's ability to undergo neural wiring and re-wiring changes over the years. Critical periods of neural development are not simple. The cortex matures in stages/columns, and the level of maturity depends on the richness of sensory exposure (Merzenich, 2010). Level one of the cortex matures by the time an infant is approximately 12 months of age. This first stage is the setup stage for the cortex; the brain is 'always-on'. In this period of cortical development, all it takes to develop auditory pathways is exposure to sound. The brain's task is to create a model of the culture into which it happens to have been born, and the baby learns how to manage the actions required to survive and thrive in that world.

The second stage of cortical development has the brain now controlling its own plasticity as the child masters skill after skill. These are massive learning-driven changes. Subsequent stages continue the maturational process to age 17–19 years. Neural organization is a bottom-up maturation process. The quality of the lower-level maturation, stimulation, and practice influences the quality of the higher-level maturation (Merzenich, 2010). Furthermore, attention plays a major role in activation of the auditory cortex (Musiek, 2009).

As human beings are organically designed without 'earlids', the brains of typically hearing children have exposure to auditory stimuli 24 hours a day. The brains of children with hearing loss have access to sound only when they are wearing their technologies … far less than 24 hours per day. Indeed, none of our current technologies are engineered for 24-hour use. Yet, our brains are organically designed for continuous auditory stimulation, even during sleep. Parents often report that their implanted children request to keep their implants on when sleeping.

Sleep is critical for infants because it allows their brains to coordinate stimuli, organize, and make

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sense of what was learned during the day. A standard sleep/wake cycle is needed to maintain normality of nearly all aspects of physiology and behavior (Velluti, 2008). There is an emerging understanding of the impact of a normal sleep/wake cycle on neural plasticity that emphasizes a positive relationship between normal sleep and learning (Golombek and Cardinali, 2008). During sleep, the evoked firing of auditory units never stops: it increases, decreases, or remains similar to that observed during quiet wakefulness. Therefore, it is clear that the central nervous system is continuously aware of the environment through auditory sensations. Considering that neonates and infants spend a substantial amount of time asleep, the continuous arrival of auditory sensory information to the brain during sleep may assure the normality of activity-dependent mechanisms of neural development (Velluti, 2008). Thus, to limit the function of cochlear implants/hearing aids to wakefulness may have important consequences on brain plasticity and neural growth.

If the family's desired outcome for their child is listening, spoken language, and literacy, then normal maturation of the central auditory pathways is a precondition for those outcomes (Sharma and Nash, 2009). It is important to recognize that 95% of children with hearing loss are born to hearing/speaking families, and the vast majority of those families are very much interested in their child communicating efficiently through spoken language within their family and community constellations.

Translation of basic cortical research to practical application in therapy

Studies in brain development show that sensory stimulation of the auditory centers of the brain is critically important and influences the actual organization of auditory brain pathways (Boothroyd, 1997; Berlin and Weyand, 2003; Chermak *et al.*, 2007). Furthermore, neural imaging has shown that the same brain areas – the primary and secondary auditory areas – are most active when a child listens and when a child reads. Phonological or phonemic awareness, which is the explicit awareness of the speech *sound* structure of language units, forms the basis for the development of literacy skills (Strickland and Shanahan, 2004; Tallal, 2004; Pugh, 2005; Robertson, 2009).

The auditory cortex is comprised of a number of functionally and structurally discrete Brodmann's areas. These areas are firmly interrelated and together characterize one functional unit (Kral and Eggermont, 2007). Lower-order areas activate higher-order areas showing bottom-up interactions and higher-order areas modulate those below demonstrating top-down interactions (Kral and O'Donoghue 2010). Anything we can do to access and 'program' those critical and powerful auditory centers of the brain with acoustic detail will expand children's abilities to listen, learn spoken language, and read. As Robbins *et al.* (2004) contend, early and ongoing auditory intervention is essential.

How do we create a hearing brain, and then teach it to be a listening brain? In order to change the cortex, attention and working memory must be controlled and training needs to commence in acoustically favorable conditions – 'Muddy in, Muddy out' (Doidge, 2007). Extensive auditory practice creates the neurological foundation not only for spoken language and literacy skills, but also for the executive functions necessary for social/cognitive development.

Early intervention: practice, practice, practice

Skills mastered by the child as close as possible to the time of intended biological pre-programming result in developmental synchrony (Robbins *et al.*, 2004). Children are organically receptive to developing specific skills during certain times of development. If those skills can be accessed and supported at the intended point in time, a developmental rather than a remedial paradigm of intervention will be in effect because we are working harmoniously with the child's structure. Furthermore, mastery of any developmental skill depends on *cumulative practice;* each practice opportunity builds on the last one. The more delayed the age of acquisition of a skill, the farther behind children are in the amount of cumulative practice they have had to perfect that skill. The same concept holds true for cumulative auditory practice. Delayed auditory development leads to delayed language skills and both deficits will necessitate using a remedial rather than a developmental intervention paradigm.

The brain demands many practice opportunities to develop neural connections. Becoming expert in a skill means that the brain has developed specialized connections through repeated practice (Pugh *et al.*, 2006). Experience-dependent plasticity is the critical concept which means that repeated auditory stimulation leads to stronger neural connections (Kilgard, 2006).

Neuroplasticity, the ability of the brain to develop neural connections with repeated stimulation, is greatest during the first $3\frac{1}{2}$ years of life; the younger the infant, the greater the neuroplasticity (Sharma and Nash, 2009). Because the infant brain develops its patterns of activity rapidly, prompt intervention in the case of hearing loss is required. Typically, this includes amplification and a program to promote auditory skill development (Clinard and Tremblay, 2008). In the absence of sound, the brain organizes itself differently so as to receive input from other senses, primarily vision. This process, called 'cross-modal re-organization,' reduces auditory neural capacity. Early amplification or cochlear implantation stimulates a brain that has not yet been reorganized, thereby allowing it to be more receptive to auditory input, resulting in greater auditory capacity.

Early auditory access allows for the many auditory and language practice sessions that the brain requires for neural growth that serves as the foundation for literacy.

Malcolm Gladwell (2008) states that 10 000 hours of practice is needed to become expert in a skill. Hart and Risley (1999) found that by the age of 4 years, typical children need to have heard 46 million words to be ready for school. Dehaene (2009) reports that 20 000 hours of listening are necessary in infancy and early childhood as a basis for reading. Are these targets possible for children with hearing loss?

What does it take to develop auditory brain centers to reach the listening, speaking, and literacy outcomes desired by most families?

Zupan and Sussman (2009) found an overall auditory preference in young children's sensory perception regardless of hearing status and a visual preference in the perception of adults. These results are consistent with those of Robinson and Sloutsky (2004). However, another study by Schorr *et al*. (2005) indicated that, unlike typical hearing children who demonstrated an auditory preference, children with hearing loss tended to rely on the visual portion of a mismatched audiovisual stimulus in processing. However, training and communication modes were not considered or discussed when evaluating perceptual preferences in this study (Schorr *et al*., 2005).

The similar degree of auditory responses in children with profound hearing loss who used cochlear implants and received auditory – verbal intervention to children with normal hearing lends support to an auditory focus for intervention paradigms (Zupan and Sussman, 2009). If typical infants and young children are organically designed to prefer auditory stimuli when processing sensory information, then auditory approaches to training for children with hearing loss may support their learning. Auditory training approaches perhaps contribute to preservation of the auditory function of primary and secondary cortical areas, instead of those neural areas being used less efficiently for visual tasks.

Summary

Hearing loss is primarily a brain issue, not an ear issue. Human beings are organically designed to listen and talk if we can stimulate auditory neural tissue with sufficient quality and quantity of sound. Technology such as cochlear implants and hearing aids are necessary to reach the brain of a child with hearing loss in order to create a neural structure for listening, language, and literacy. The brain requires a great deal of auditory exposure and practice to develop the strong neural connections that serve as a platform for knowledge acquisition. Therefore, an integrated service delivery model is required for infants and children with hearing loss who use today's technologies, featuring auditory-focused intervention designed to offer thousands of hours of listening and spoken language practice opportunities.

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