The Role of Sound in Normal Cognitive Development

The newborn's brain comes ready to organise and develop. A major stimulus that drives this organisation is sensory input, especially input that is consistent and relevant (Merzenich, 2010). Audition, of course, one of the major sources of this crucial stimulation.

Here are a few examples of the way sensory input early in life affects cognitive development:

Auditory stimulation before birth can affect how the child responds to native versus non-native language: As the child develops in utero, auditory stimulation is reaching the developing auditory system. Work by Partenen et al. (2013) and DeCasper & Fifer (1980) has shown evidence that newborns will already show a preference for the language that they experienced while in utero, presumably transferred from the mother's voice through her body (Smith et al., 2003).

The brain eliminates irrelevant connections during development: Corel (1975) reports that the number of synapses increases from birth up to 2 to 3 years of age, but then declines again into adulthood, presumably due to a "pruning" of unnecessary innervation patterns. It is known that between 6 and 10 months of age, the infant's ability to discriminate between native speech sounds improves, whereas the same ability to discriminate between foreign speech sounds decreases. Adult native speakers of Japanese, for example, have great difficulty in discriminating between words containing English /r/ and /l/, phonetic segments that belong to the same underlying category in Japanese, since that was irrelevant information for them as infants (Kuhl, 1992).
Our abilities are also shaped by the stimuli we receive as infants: For example, infants discriminate monkey faces more efficiently than adults – a skill the brain eventually considers unnecessary if we do not grow up seeing different monkeys every day (Pascalis, 2002). In this case, our visual perceptual preferences narrow in on our own species.

Stimulation during development can improve adult perceptual skills: Even very brief exposure to specific sounds during development may enhance adult perceptual skills. This has been best illustrated by experiments where animals are actively engaged in learning, and especially when natural communication sounds are involved (Sanes et al, 2011).

Kang et al (2014) found that hearing-impaired animals trained for 10 days during development displayed thresholds closer to untrained normal hearing adults, than those trained for 4 days. Thus, a relatively brief period of auditory training may compensate for the damaging impact of hearing deprivation on auditory perception on the trained task.

Sound must be consistently available for the normal course of development to take place

Keating et al (2014) also found evidence that spatially trained ferrets performed better on a localisation task if they were trained during development - highlighting the importance of sensory experience for shaping the underlying neural mechanism of using different sound localisation cues.

Learning via the auditory modality, both formally and informally, starts at birth and even before. Sound must be consistently available for the normal course of development to take place.

Auditory Physiological Development
We are born with a full neural network in the brain - but not the fully developed connections. The capacity is there, but it requires further maturation. The more neural pathways are used in a consistent manner, the stronger the connections.

By the age of 6 the brain has generally reached its adult volume (Vannucci et al, 2011). However, the anatomical maturation is not complete until 11-12 years of age (Moore & Linthicum, 2007) and the functional organisation of local nerve cell networks and connections between brain regions extends well into the teenage years. This extended maturation of the brain involves branching of neurons, synaptic trimming and strengthening as well as axonal myelination. Of functional importance at this developmental stage, where basic sensory processing is largely in place, is the integration of information from several perceptual modalities. Even normal hearing 13-year-olds have not peaked at gaining from a combined auditory and visual signal. Multisensory integration of speech input is an ability which is crucial for effective communication and has a major impact on performance in the classroom and in social settings (Velanova et al., 2009). Further, recordings from the temporal areas of the cortex indicate functional changes in both speech and tone processing in 10 to 18 year old children (Mahaja & McArthur, 2013). Complex functions such as suppressing task-irrelevant stimuli are developing far into adulthood (Velanova et al, 2009).

The implication of this work is that the development of the auditory system continues throughout childhood, adolescence and into adulthood.

Our Expanding Understanding of the Brain:
New evidence show that structures in the brain not belonging to the auditory system have been found responding to sound (Moore, 2012). These cortical areas have joint
connection with the recognised auditory system and thus form the origin of the ‘top-down’, descending, ‘efferent’ auditory system, with these descending pathways being implicated in functions such as binaural processing and auditory learning. These “top-down” areas generally develop later than the “bottom-up” structures (Herdman, 2011; Moore, 2012). This is particularly relevant when we consider the specific auditory perception abilities used by children when faced with challenging listening environments, for example, a noisy classroom, with poor signal to noise ratio, lots of distraction and the need to follow complex instructions. These are situations where we adults use a significant amount of “top-down” processing that has not developed fully in the child’s brain. Such environments are particularly demanding for a child with impaired hearing (Shinn-Cunningham & Best, 2008).

**Brain plasticity - changes in mapping and weighting:**
A recent study has shown that, depending on resources available, brains of ferrets are flexible in their use of monaural and binaural cues on a spatial hearing task (Keating et al, 2013). When hearing declines in one ear, so that the binaural cue information changes, one potential effect could be that the hearing system could recalibrate to a new zero for timing and intensity differences. Evidence of this remapping has been found in barn owls (Knudsen, 1985). In this way the auditory system could still use these new abnormal binaural cues to localise sounds in space. Another strategy for adapting to the new or unavailable binaural cue information could be to compensate with using more of other cues. It is known that monaural spectral cues can also be used for localising sounds in space. These cues are thought to be especially helpful in determining whether sound is coming from the front or rear hemifields and have proven to be useful when binaural cues are absent (Keating & King, 2013).

*The full network of neurological connections is established as a result of consistent, long-term sensory stimulation*

Keating et al (2013) had one ear temporarily plugged on ferrets and showed that they used a greater amount of monaural cues when binaural cues were absent. Along with performance measures showing this change, neuronal responses in the primary auditory cortex also showed that they became relatively more sensitive to these monaural spatial cues. But after they regained normal function in both ears they were able to use binaural cues again and the changes in neural reweighing disappeared. Keating et al (2013) name this spatial bilingualism - since it is similar to having access to two different languages.

**Sensory Deprivation**

**Sensory Deprivation and Critical Periods:** It was believed for a long time that when hearing was lost, that meant a permanent loss of function. This assumption was partly confirmed by studies of blindfolded cats which experienced sensory deprivation of sight during the first 3 months of life. After the blindfolds came off they could never regain sight (Hubel & Wiesel, 1965).

However, in later studies it was found that it mattered when the cat had been blindfolded and for how long the visual function was affected. Thus, critical and sensitive periods during maturation are very important for normal development of sensory function.

We know now, after successful cochlear implantation in infants, that children actually can hear again after periods of total deafness. But what periods are critical for different types of sensory function, which functions are affected by sensory deprivation and how to best stimulate to avoid as much sensory loss as possible, are still current research topics.

**The Complex Effects of Auditory Deprivation:** Children with cochlear implants have been found to differ from normal hearing children in their capacity for sequencing visual information. The implanted children obtained worse scores than normal hearing children on tasks where they were asked to reproduce colour patterns that they had just been exposed to. This is believed to be due to a period of auditory deprivation occurring before the child was implanted, presumably affecting the infant looking behaviour (Conway et al 2011).

The relationship between individual differences in language learning and looking behaviour during audiovisual speech integration in infants has also been found to predict auditory speech comprehension in the second year of life. Visual sequence learning abilities are therefore believed to be important factors in language development (Kushnerenko et al, 2013).

Motor skills are necessary for complicated movements such as speaking or playing the piano. A recent study indicates that deaf individuals can experience significant reduction in this ability. Profoundly deaf individuals (most from childhood) showed significantly worse results in a task where they pressed a key on a keyboard corresponding to the position of an asterisk on a wall, as fast as possible, with the task appropriate finger (Lévesque et al 2014).

Disordered hearing leads to an incomplete maturation of the natural neurological organisation of the brain, not just...
in the auditory areas but in many associated locations. Incomplete or inaccurate auditory input can have effects on many aspects of the child’s life, including speech and language development, educational achievement, socialisation, listening effort and fatigue, amongst others (e.g., Jerger, 2007).

**Early provision, verification and validation of amplification is crucial to pave the way for the development of language abilities**

**Minimising the Threats to Cognitive Development**

Successful, early amplification can affect many aspects of the child’s life. Many studies in recent years have studied these beneficial effects. For example, early amplification has shown positive effects on communication abilities (Sininger et al, 2010). Johnstone et al (2010) also investigated how well hearing aids could restore balanced hearing to children with sensorineural hearing loss in one ear. Children who received hearing aids early in life (< 5 yrs) demonstrated improved aided sound localisation compared to those who received aids later in life.

Early provision, verification and validation of amplification is crucial to pave the way for the development of language abilities. Koehlerling et al (2013) found that after age, aided SII (Speech Intelligibility Index) and age at amplification were the best predictors for grammatical outcomes in children with hearing loss. Ching et al (2013) found that evaluation of language and functional performance directly after first amplification was one of the factors predicting language outcomes later in life.

These and many other studies emphasise the value of early and appropriate amplification in order to provide the child with hearing loss with access to the stimulation needed to support the acquisition of speech and language abilities, among other important developmental skills.

**Importance of early and appropriate amplification for cortical maturation**: If cochlear implants are obtained early in life, cortical recordings of the P1 and N1 waves have even been found to be restored and normalised. This is quite astonishing since these cortical responses are usually absent in deaf children and often used as biomarkers for normal auditory maturation. However, if cochlear implants are obtained after 4 1/2 years of age the N1 wave might not even develop, and the arrival time of the waves will never occur within normal time windows.

Lately, studies are emerging that hard of hearing children/adolescents, despite intervention, are disadvantaged compared to normal hearing children at high-level cognitive functions such as empathy (Netten et al 2015) or executive function (Kronenberger et al 2014). Executive function encompasses working memory, controlled attention, novel problem solving, planning, organisation, and mental efficiency and speed. These fundamental neurocognitive processes appear to be particularly vulnerable to the effects of auditory deprivation.

**Provision of solutions that provide a consistent, complete and accurate reflection of sound can help to minimise the threats to cognitive development created by the presence of hearing loss**

**The Oticon BrainHearing™ Approach**

The presence of hearing loss puts the growing child at great risk of delays and disruptions in cognition-mediated areas such as speech, language, educational and social development. At Oticon, we have a specific focus on developing technologies and intervention approaches that support the broad range of cognitive development in the child. We call this approach BrainHearing™.

**It is essential to provide the brain with the most enriched, complete and consistent signal as possible in order to create the best opportunity for full cognitive development**

A core tenet of this approach is that, not only is it essential to properly compensate for the peripheral effects of hearing loss, but it is also essential to provide the brain with the most enriched, complete and consistent signal possible in order to create the best opportunity for full cognitive development.

We believe that the signal that the child receives must provide an accurate reflection of the world of sound. Of course it is important to provide full access to the speech signal across a full range of inputs and a full frequency range. However, this aided signal must also best preserve the details of sound that will be most useful to the cognitive system. This includes not only attempting to provide an excellent signal-to-noise ratio, but also preserving the intricate details of the complex speech waveform. Finally,
if the hearing aids are not available for the child on a regular basis, then excellent signal processing and fitting approaches make no difference. To that end, a reliable and safe design is essential, which may instill confidence in parents and improve wearing compliance.

What is BrainHearing™ Technology?
In order to fully support cognitive development, amplification must meet three important criteria:

Provide full access to the speech signal:
• **Extended Bandwidth**: the speech signal includes important phonemic information well past 4 kHz. We have created products with the capability to provide audibility for many children with hearing loss for these crucial, high frequency speech sounds (e.g., Kimlinger et al., 2015).
• **Wide Dynamic Range**: We are fully compatible with the audibility recommendations of the DSL 5.0 fitting rationale. We recognise the need to provide access to speech across a broad range of input levels that the child will encounter on a daily basis.

Processes speech in the smartest way possible:
• **Speech Guard E**: When implementing a nonlinear fitting rationale, the behaviour of the compression system in response to natural changes in the speech signal can potentially restrict important information. Speech Guard E is specifically designed to preserve as much of the naturally occurring information in the speech signal as possible. The value of this approach to nonlinear processing has been demonstrated by Pittman et al (2014).
• **Voice Priority i**: In school, VPi is designed to automatically adjust the level of the teacher’s voice at the child’s ear when the noise level in the classroom rises. The goal is to preserve the excellent signal-to-noise ratio created by the FM system. The effectiveness of this approach has been recently verified by Schafer (2013).
• **FreeFocus Directionality**: Outside of school, automatically helps defeat the effects of background noise with a unique, outcome-based approach to determining when directionality is useful for the child.

Deliver sound without interruption:
• **LED**: Oticon pioneered the concept of placing an LED light on the hearing aid to alert parents, teachers and other caregivers to the functional status of the device.
• **Robust Paediatric Design**: Great care is taken in the design and manufacturing of the devices to provide a safe and reliable product. All Oticon paediatric devices have earned the stringent IP58 rating.

If sound is going to be used as part of cognitive development, it needs to be complete, accurate and consistent. We strive to help make sound a source of information the developing child with hearing loss can depend upon

Final Thoughts
Child are born with an amazing capacity to constantly soak up information about the world around them – what is out there, how does it work, how do I fit into it? Hearing is one of the primary sources of this information. Hearing loss makes it quite challenging for the child to fully discover how the world works. Our goal, working through the audiologist, is to create solutions that allow each and every child to develop – to learn, to integrate with family, friends and society, to be successful – to the greatest degree possible.
References


Our paediatric audiological mission is to ensure a better future for every child with hearing loss. We will deliver solutions, tools and techniques that optimise auditory and cognitive habilitation, embrace the complexities of growing up with hearing loss and empower you to adapt solutions to each child's developmental stage on their journey to adulthood.

People First is our promise to empower people to communicate freely, interact naturally and participate actively.

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