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Review

# Adaptation of the communicative brain to post-lingual deafness. Evidence from functional imaging

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A B S T R A C T

Not having access to one sense profoundly modifies our interactions with the environment, in turn producing changes in brain organization. Deafness and its rehabilitation by cochlear implantation offer a unique model of brain adaptation during sensory deprivation and recovery. Functional imaging allows the study of brain plasticity as a function of the times of deafness and implantation. Even long after the end of the sensitive period for auditory brain physiological maturation, some plasticity may be observed. In this way the mature brain that becomes deaf after language acquisition can adapt to its modified sensory inputs. Oral communication difficulties induced by post-lingual deafness shape cortical reorganization of brain networks already specialized for processing oral language. Left hemisphere language specialization tends to be more preserved than functions of the right hemisphere. We hypothesize that the right hemisphere offers cognitive resources re-purposed to palliate difficulties in left hemisphere speech processing due to sensory and auditory memory degradation. If cochlear implantation is considered, this reorganization during deafness may influence speech understanding outcomes positively or negatively. Understanding brain plasticity during post-lingual deafness should thus inform the development of cognitive rehabilitation, which promotes positive reorganization of the brain networks that process oral language before surgery.

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## 1. Introduction

Not having access to one sense profoundly modifies interactions with the environment (Merabet and Pascual-Leone, 2010; Strelnikov et al., 2010). Advances in functional imaging (Friston, 2009) and animal models (see Kral et al., 2013 for a review) have contributed to the exploration and better understanding of sensory deprivation, especially illuminating the effect of deafness on brain adaptation. Sensory deprivation leads to modifications in relative connectivity between cortical areas, and particularly in interactions across sensory areas, depending on the age at which the deprivation occurs (for a review, see Merabet and Pascual-Leone, 2010). In both humans and animals, the loss of one sensory modality induces compensatory mechanisms leading to increases in performance of the spared modalities (for reviews, see Bavelier et al., 2006; Rauschecker, 1995; Röder and Rosler, 2004). Among the sensory losses, deafness causes significant handicap as it prevents social interactions through oral communication. Helen Keller who was deaf–blind used to say that “Blindness separates people from things, deafness separates people from people”.

Thanks to sign language (visual-based communication) and cochlear implantation (which provides the brain with auditory inputs through electric stimulation), models of sensory deprivation, adaptation and re-afferentation have allowed great steps in the understanding of brain plasticity in pre- and post-lingually deaf subjects. The distinction between pre-lingual and post-lingual deafness is important because learning a language is a long

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process that starts peri-natally in people with normal hearing (Dehaene-Lambertz et al., 2002). Hearing experience during the first year of life (phonemic contrasts in particular) drives brain maturation and central physiological organization related to speech perception and production (see Kral, 2007 for a review). Using a variety of brain imaging methods, it has been shown that the congenitally-deafened brain does not show the same developmental organization as a brain that is exposed to normal auditory inputs from birth to the age of approximately 5 years, when the basics of language are considered acquired and language learning tends to stabilize (Bavelier et al., 2001; Fine et al., 2005; Finney et al., 2001).

The effect of non-rehabilitated pre-lingual deafness on the remaining visual and somatosensory senses (Bavelier et al., 2006; Dye and Bavelier, 2010), as well as auditory development after cochlear implantation in childhood (Kral and Sharma, 2012; Sharma et al., 2009, 2007) has been previously reviewed. The effects are complex and vary depending on the compensatory modality, state of development, and individual factors (Kral and O'Donoghue, 2010). We provide here a brief overview of the findings concerning central modifications related to congenital deafness, but will subsequently focus on reorganization related to oral communication in post-lingually deaf adults. Developmental studies show that a high potential for plasticity exists within the first 3 years after birth and that the brain takes advantage of the senses available by potentiating them (Bavelier et al., 2006). During this developing period, competition between the dominant senses determines final differentiation within multi-sensory areas (Levanen et al., 1998). If one sense is missing, such as hearing, the spared modalities are boosted, leading to supra-normal compensation (Bavelier and Neville, 2002; Bavelier et al., 2006). Thus, in congenitally-deaf subjects, enhanced spatial attention and reactivity to visual events presented mainly in the peripheral visual field have been observed (Bavelier et al., 2006; Dye and Bavelier, 2010; Neville and Lawson, 1987). The beneficial changes in visual skills are however selective to traits that normally interact with available auditory input during audio–visual convergence (see Bavelier et al., 2006 for a review). So deaf individuals generally do not exhibit better performance in simple visual discrimination tasks. Once the sensitive period of plasticity is over, after the age of 7 years, specific organizations/specializations may not be reversible. This phenomenon has been related primarily to extensive synaptogenesis between 2 and 4 years of age, followed by synaptic elimination (central pruning) from 4 to 16 years (Huttenlocher and Dabholkar, 1997). Consequently, brains deafened for too long may not allow satisfactory auditory rehabilitation by a cochlear implant (CI) if surgery occurs after the end of the sensitive period (Giraud and Lee, 2007; Lee et al., 2005, 2007b; Sharma et al., 2009; Sharma et al., 2007).

After the sensitive period is over, primary and secondary auditory areas are no longer able to develop new functional interactions, even though the CI provides auditory inputs. Non-auditory functions, such as sign language processing (Lambertz et al., 2005; Nishimura et al., 1999), may be observed in the secondary auditory areas, and in the case of late implantation, auditory activations have been observed in visual and parieto-temporal areas without any benefit to speech comprehension (Sharma et al., 2007, 2009). Further, early deafness likely affects top–down influence (from high-order areas), leading to the functional decoupling of primary auditory cortex (Kral and Eggermont, 2007). The decrease of top–down modulation in deafness seems to negatively impact on related high-level abilities, such as auditory object categorization, or attentional processes (Kral and Eggermont, 2007).

The same principle applies to non-deprived brains: functional organization tends to be permanent, even though some plasticity and reorganization are possible in adulthood due to lesions (e.g. Cramer et al., 2011; Kell et al., 2009; van Oers et al., 2010) or post-lingual deafness (Lazard et al., 2013; Rouger et al., 2012). Because most cognitive functions are asymmetrically implemented in the brain (Formisano et al., 2008; Hickok and Poeppel, 2007; Hugdahl, 2000), engaging the contralateral cortex to palliate deficits or injury in language processing may be less efficient than the primary functional organization, and hence maladaptive (Kell et al., 2009; Marsh and Hillis, 2006; Naeser et al., 2005; Preibisch et al., 2003; van Oers et al., 2010).

Based on the idea that deafness impoverishes social interactions, principally when it occurs in subjects who were used to hearing (post-lingually deafened), this review will focus on functional imaging findings concerning central adaptation to oral communication loss induced by post-lingual deafness (for animal models, refer to Kral et al., 2013). We hypothesize that central repurposing is driven by communication needs. To understand the observed reorganizations, the physiology of speech perception and reading will be examined. Evidence of adaptation to acquired deafness and its consequences on the observed variability in speech understanding once post-lingual subjects have received a CI will be reviewed.

## 2. Prerequisites

To understand plasticity, a few terms need to be defined. *Multi-modal* brain areas receive and process inputs from different modalities. *Intra-modal* reorganization/plasticity refers to the potentiation of dedicated areas (uni-modal areas) in their usual modality or function (e.g. increased activity within the visual cortex during lip-reading, a communication relying on visual inputs (Doucet et al., 2006)). *Cross-modal* reorganization/plasticity refers to cortical areas that become under-stimulated by their usual sensory inputs and are taken over by other modalities (e.g. activation of auditory areas by sign language (Finney et al., 2001)). *Meta-modal* reorganization/plasticity applies to originally multi-modal sensory areas that come to favor one modality (or several modalities) over another modality, when sensory input in this latter modality is reduced.

Except for very limited specific etiologies for which subjects become abruptly profoundly deaf (meningitis, bilateral temporal bone fracture, bilateral sudden idiopathic hearing loss), post-lingually deaf people usually face a period of progressive hearing deterioration from moderate to profound deafness (from a pure tone average loss of 40 decibels (dB HL) to 90 dB HL). The duration of moderate hearing loss is defined as the time from which the pure tone average hearing loss is more than 40 dB HL, and/or the time of the first use of hearing aids, until the time of severe to profound deafness. When people become severely or profoundly deaf, they may become a candidate for a CI (UKCISG, 2004). This period of progressively worsening hearing has been minimally investigated in functional imaging studies, which generally focus on the period of total auditory deprivation. However, in a large sample of post-lingual CI recipients, we have shown that the duration of moderate hearing loss impacts CI outcome negatively (Fig. 1) (Lazard et al., 2012b). This study also showed that hearing aids may improve post-implantation speech understanding if worn during the period of severe to profound hearing loss. Wearing two hearing aids pre-implant was related to better post-implant speech outcomes than not having any hearing aid, suggesting that even minimal stimulation tends to preserve auditory functions and areal specificity (Lazard et al., 2012b). The hypothesis is that hearing aids have a protective effect against deleterious plasticity such as visual take-over of auditory areas (Doucet et al., 2006). These factors may